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TEST AND EVALUATION OF NIGHT VISION OPTICAL SYSTEMS: THIRD GENE--ETC(U)

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TEST AND EVALUATION OF NIGHT VISION OPTICAL SYSTEMS

Third Generation Goggle Objective Lens

Baird-Atomic, Inc.
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June 1977

Prepared for

DEPARTMENT OF THE ARMY
UNITED STATES ARMY ELECTRONICS COMMAND
NIGHT VISION LABORATORY
ATTN: DRSEL-NV-VI
Fort Belvoir, Virginia 22060

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Four objective lens designs for third generation (GEN III) image intensifier tubes are analyzed. The lenses are coupled to the 0.225-inch thick photocathode faceplate of GEN III tubes and optical performance is studied in the response region from 0.7μ to 0.9μ. Other aspects of design considered in overall evaluation include projected manufacturing costs, as well as the size and weight of the lenses. Based on the data contained in this report, recommendations are presented for the further development of third generation night vision optical systems.

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FIGURES

TABLES

1. INTRODUCTION

1.1 GENERAL

Third generation (GEN III) image intensifier tubes operate in a narrow spectral region and use a thick, low index glass faceplate (Corning 7056), rather than the conventional fiber optic faceplate of first and second generation tubes. This report analyzes the impact of this design in the area of goggle objective lens systems.

Evaluation proceeds on two levels. The first task examines the possibility of using the AN/PVS-5 goggle objective lens both "as is" and in a modified state with GEN III tubes. The second task looks at two alternate designs. One design is similar to the current objective lens configuration, while the other is an all new approach with lower cost and weight heavily favored. Based upon the results, conclusions are drawn and comparisons made, leading to recommendations for use as guidelines in the development of GEN III goggle systems.

1.2 APPROACH TO COLLECTION OF EVALUATION DATA

1.2.1 AN/PVS-5 Evaluation

To provide a reference for comparison, the AN/PVS-5 18-mm goggle objective is evaluated as it presently operates with GEN II image intensifier tubes. This evaluation is performed in the wavelength range from 0.5μ to 0.8μ.

1.2.2 Task 1 Evaluation

The aberration and color characteristics of the 0.225-inch image intensifier tube faceplate are examined in relation to the original objective's performance. A full examination, involving fan plots and MTF runs, is not performed. Calculations are given which provide the information necessary to evaluate the coupling of the lens to the faceplate.

A partial modification of the AN/PVS-5 goggle objective lens is also carried out, paying close attention to restrictions on dimensions, weight, and manufacturing costs. To minimize changes from the current system, the image intensifier tube faceplate is considered to be variable. Glass substitutions are made only where optically necessary. The intent is to optimize the lens performance with a minimum of changes. Evaluation of the system is in the spectral region from 0.7μ to 0.9μ, in accordance with the GEN III tube response.

1.2.3 Task 2 Evaluation

Full modification of the AN/PVS-5 objective is performed with all curvatures and spacings variable. Curvature of the intensifier tube faceplate is avoided, and more freedom is taken in glass choice. The goal is to modify the existing objective into an alternative configuration which optimizes performance where a partial modification falls short.

A new objective lens for use with the GEN III tubes is analyzed. A Baird-Atomic objective lens which is lightweight, short, simple in configuration, and inexpensive--yet suitable in optical quality--is used. This is a demonstration of the feasibility of designing a lens which meets the above criteria.

All evaluation data for this task are prepared in the GEN III response region from 0.7μ to 0.9μ.

2. EVALUATION

2.1 GENERAL

For each of the systems, 1:1 and 2:1 scale lens plots are provided to show on-axis and full field ray traces. In addition, ray trace fan plots (aberration curves) in primary (P), secondary (S), and tertiary (T) light, and geometric MTF plots and system calculations are presented. Appendix B contains a list of the abbreviations which apply to the calculations pages. Lens prescriptions for the AN/PVS-5 goggle objective--in its present design, as well as under partial and full modification--are provided in Appendix A.

A left-handed coordinate system (Figure 1) is the convention for all the plots, calculations, and discussions in this report.

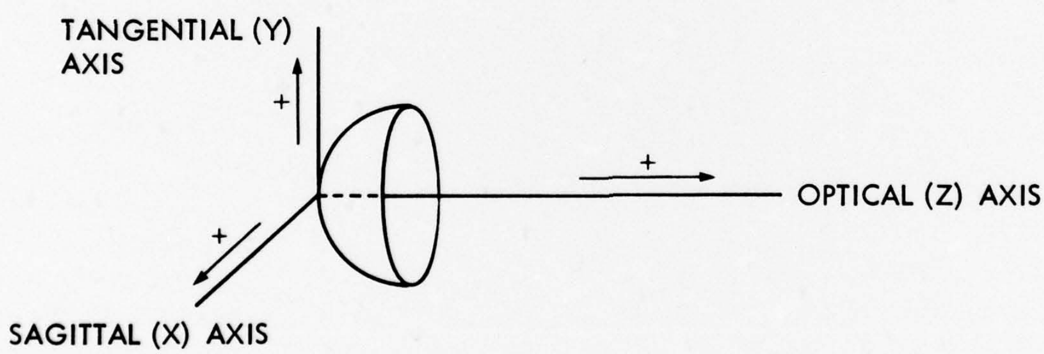


Figure 1. Left-handed coordinate system

Light rays originate from an object to the left and travel in the positive Z direction. Optical surfaces are numbered increasingly from left to right with the first surface numbered one (1). Optical elements are similarly numbered, with compound elements having alphabetic subscripts (example: AN/PVS-5 triplet is compound element 4 with individual elements 4A, 4B, and 4C).

The ray trace fan plots express the change in ray intercept height as a function of fractional ray height on the entrance pupil. The intercept height of the chief ray (ray through the center of the entrance pupil) is used as a reference (Figure 2).

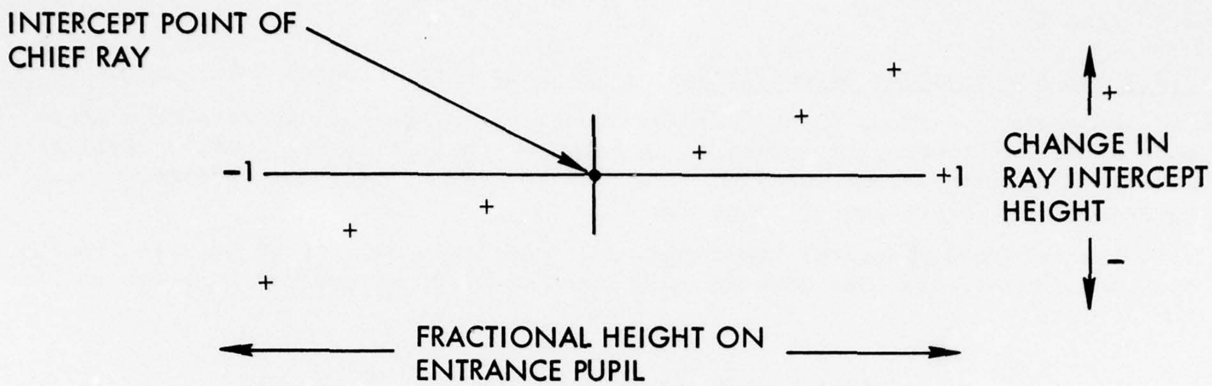


Figure 2. Ray trace fan plots

These plots may be related to the aberration coefficients given on the system calculations pages (Figures 8, 14, 20, and 26) by fifth order expansion equations. The height, y' (tangential plane), of a meridional ray at the image surface is given by:

$$y' = h'\bar{H} + (SPHR)\ Y^3 + (COMA)\ \bar{H}Y^2 + (TANG)\ \bar{H}^2Y + (DIST)\ h'\bar{H}^3 + (SPHR5)\ Y^5 + (COMA5)\ \bar{H}Y^4 + (TOBSA)\ \bar{H}^2Y^3 + (ECOMA)\ \bar{H}^3Y^2 + (TANG5)\ \bar{H}^4 + (DIST5)\ \bar{H}^5,$$

where $\bar{H}$ is the fractional object height, Y the fractional pupil height, and h' the gaussian or first order image height. Similarly, the coordinate of a sagittal ray at the image surface, x', is

$$x' = (SPHR)\ X^3 + (SAGT)\ X^3 + (SAGT)\ \bar{H}^2X + (SPHR5)\ X^5 + (SOBSA)\ \bar{H}^2X^3 + (SAGT5)\ \bar{H}^4X,$$

where X is the fractional pupil coordinate in the sagittal dimension.

The MTF results are calculated by tracing a number of rays through the lens system and analyzing the spatial distribution of their intercepts in the image plane. Weightings refer to the number of rays traced through half of the entrance pupil for a particular wavelength of light. For the AN/PVS-5 evaluation, a weighting of 40,20, 20 is used for wavelengths of 706.5 nm, 546.1 nm, and 852.1 nm respectively. This is representative of the relative response of second generation tubes. GEN III tubes have a peaked red response; therefore, all MTF's for GEN III applications are given a weighting of 40 at 800 nm, 8 at 700 nm, and 8 at 900 nm.

The total lens weights given are not to be considered exact. Ground flats on negative elements, exact outer diameters, and other engineering considerations are not incorporated into the calculations. The weights are provided for comparison purposes, to analyze the benefits of one system versus another.

2.2 TASK 1

2.2.1 AN/PVS-5 Goggle Objective With Thick Faceplate (Figures 3 Through 8)

In general, a flat, thick faceplate inserted in the optical path of a lens contributes overcorrected spherical and axial-chromatic aberrations, as well as positive astigmatism and negative coma. These lead to residual aberrations and consequent deterioration of image quality.

Overcorrected spherical aberration is immediately evident in on-axis resolution considerations. The equation for third order spherical semiblur due to a thick plate is:

$$\text{SPHR} = +\frac{1}{2}\left(\frac{n^2 - 1}{n^3}\right) \times d \times (\text{N.A.})^3$$

Here, n is the refractive index of the material, t, the thickness, and N.A., the numerical aperture of the cone of light incident on the plate. The plus (+) sign indicates overcorrection. For an f/1.35 light cone, 1.481 index of refraction (Corning 7056, λ = 852.1 nm), and 5.7-mm thickness, the third order transverse semiblur is 0.05 to 0.06 mm. Referring to the aberration coefficients of Figure 8, SPHR (third order spherical semiblur) becomes approximately 0.03 to 0.04, while SPHR5 and SPHR7 have smaller positive changes. The balance achieved during the design of the AN/PVS-5 objective for GEN II use is thus lost and severe on-axis blurring occurs. The blur circle radius can be reduced by a factor of 4 if pure third order exists, but the higher order aberrations of this problem prevent such an improvement.

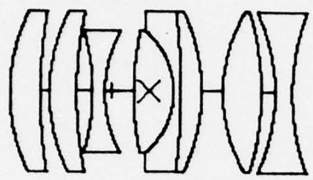
As stated, the off-axis imaging is afflicted with negative coma (negative, because the chief ray angle for off-axis points is diverging from the optical axis). The third order formula for total coma transverse blur is:

$$\text{COMA} = -\frac{3}{2}\left(\frac{n^2 - 1}{n^3}\right) \times d \times (\text{N.A})^2 \times \bar{\mu},$$

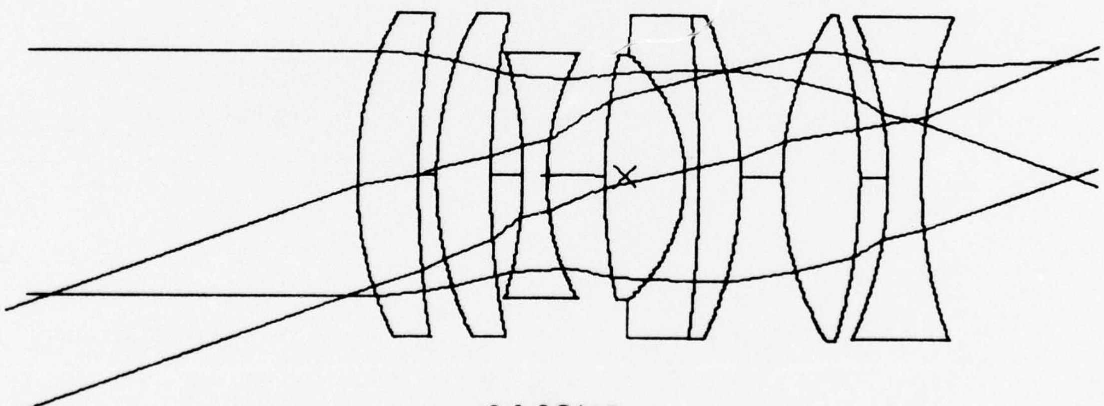
where $\bar{\mu}$ is the tangent of the full field chief ray. At 20 degrees, this amounts to -0.16 mm. The approximate effect of this on the AN/PVS-5 is visualized by adding a negative parabola having a value of -0.16 mm at 1.0 fractional pupil height to the full field fan of Figure 6. (Figure 6 is used because it is most representative of the aberrations at long wavelengths.) This coma causes the image of off-axis points to flare toward the optical axis. Add to this positive astigmatism, and the result is extreme off-axis blurring.

2.2.2 Partial Modification of AN/PVS-5 Objective With Thick Faceplate (Figures 9 Through 14)

The AN/PVS-5 GEN II goggle objective performance depends upon a sensitive aberration balance of the adjacent surfaces of elements 5 and 6. Surface 12 (element 5) contributes a large amount of undercorrected spherical aberration and negative coma, while surface 13 (element 6) counters with appropriate amounts for balance. The partial modification utilizes this in minimizing the changes necessary to establish optical quality.



1:1 SCALE



2:1 SCALE

Focal length	26.64 mm (λ = 852.1 nm)
F/no.	1.33
Field of view	40°

Figure 3. 18-mm AN/PVS-5 goggle objective lens

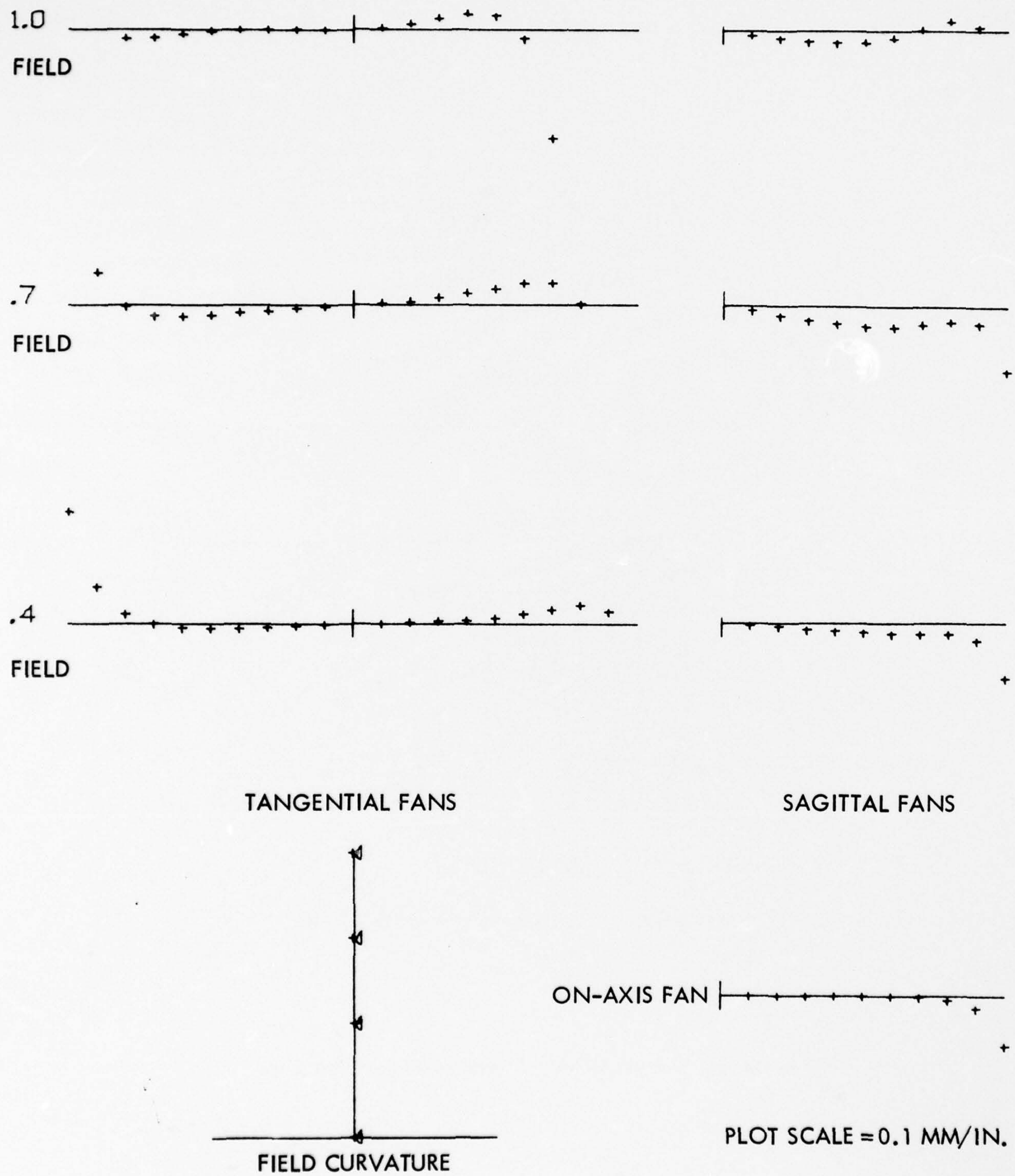


Figure 4. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for P light (706.5 nm)

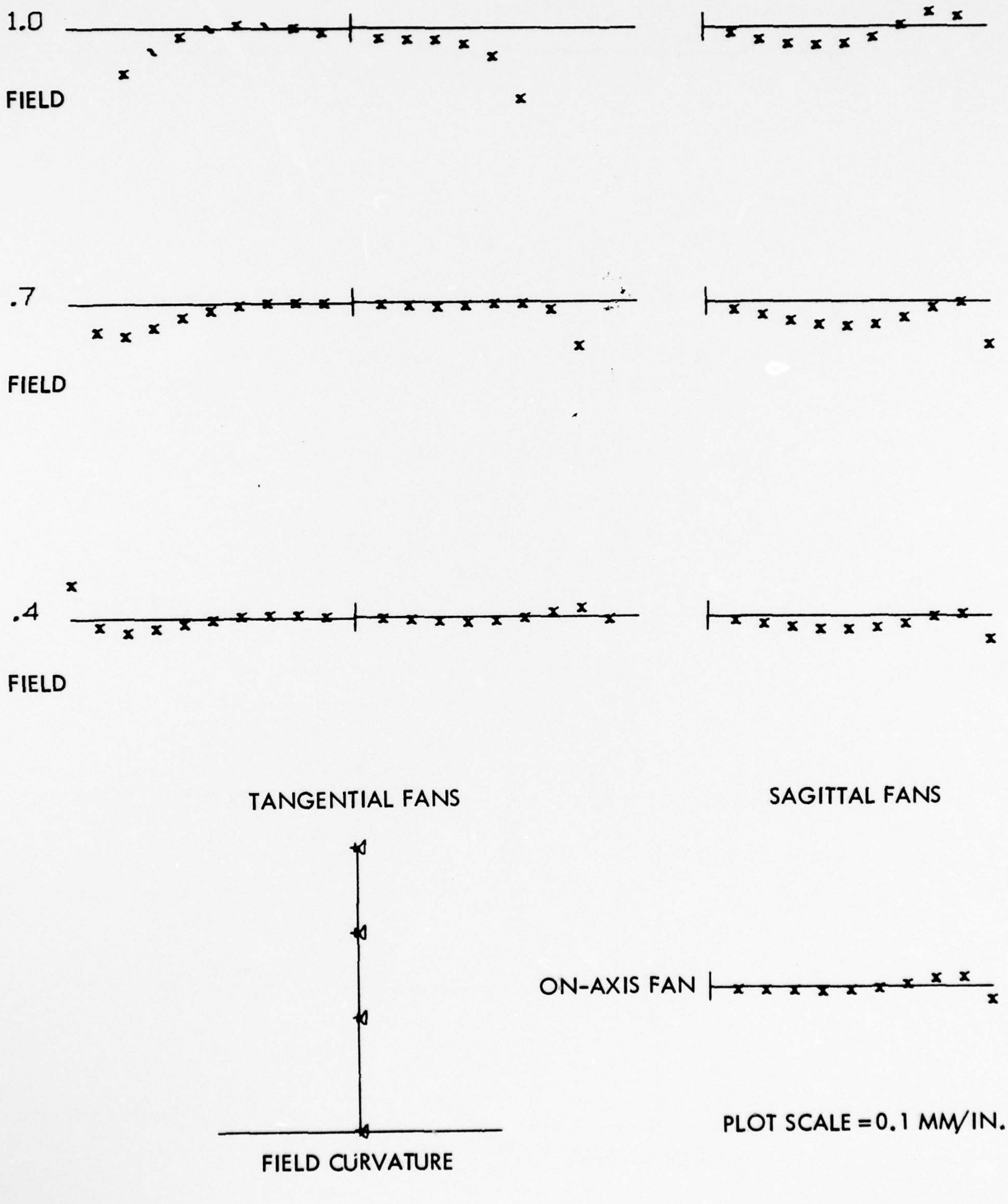


Figure 5. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for S light (546.1 nm)

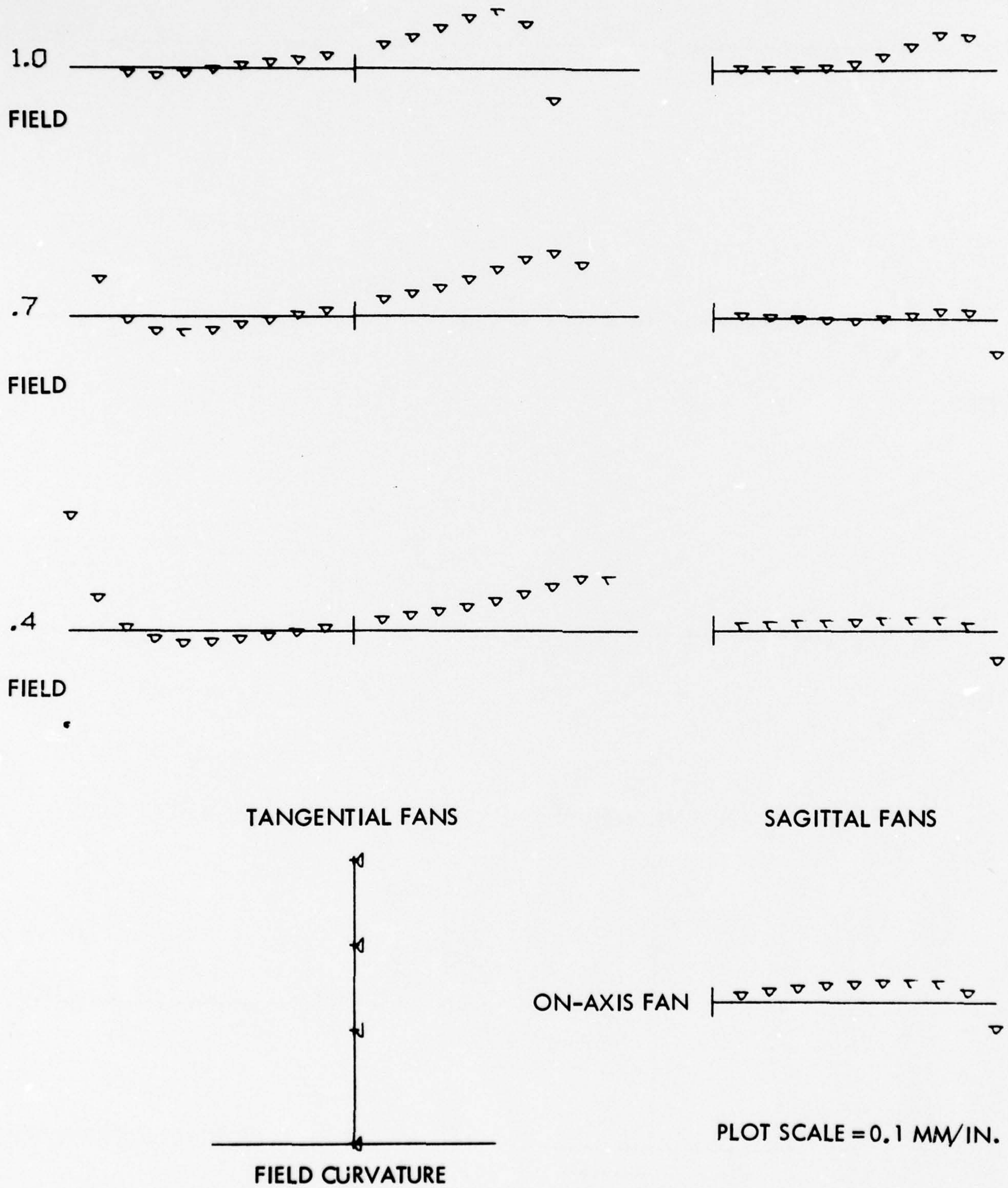
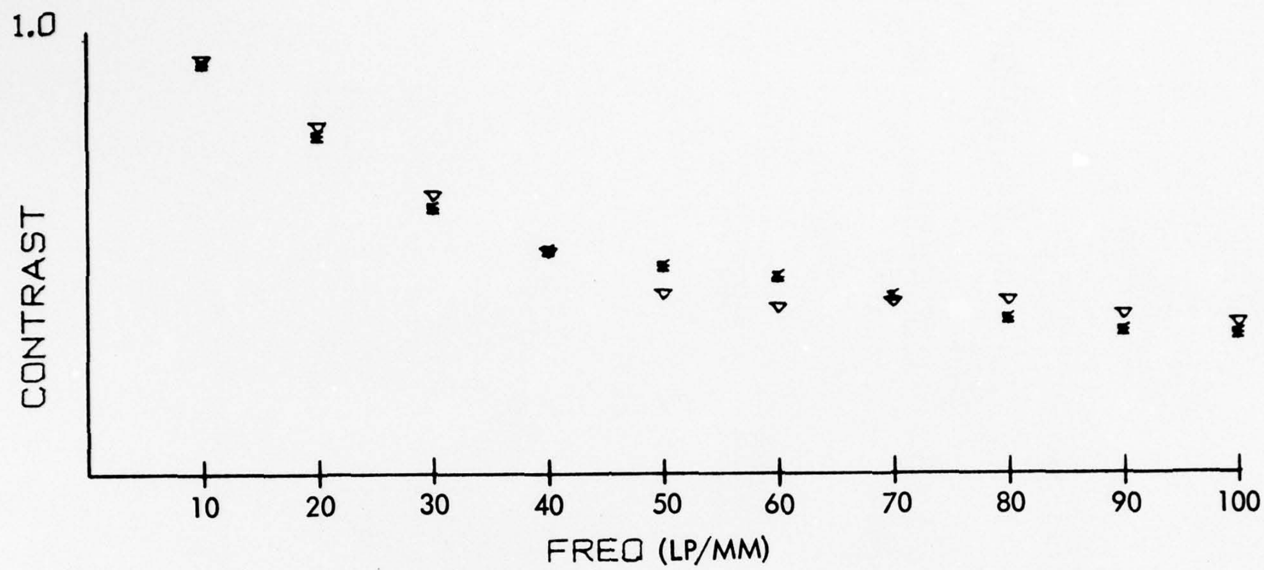


Figure 6. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for T light (852.1 nm)



		WAVELENGTH (NM)	MTF WEIGHTING
×	TANGENTIAL RESPONSE	706.5	40
+	SAGITTAL RESPONSE	546.1	20
∇	45° RESPONSE	852.1	20

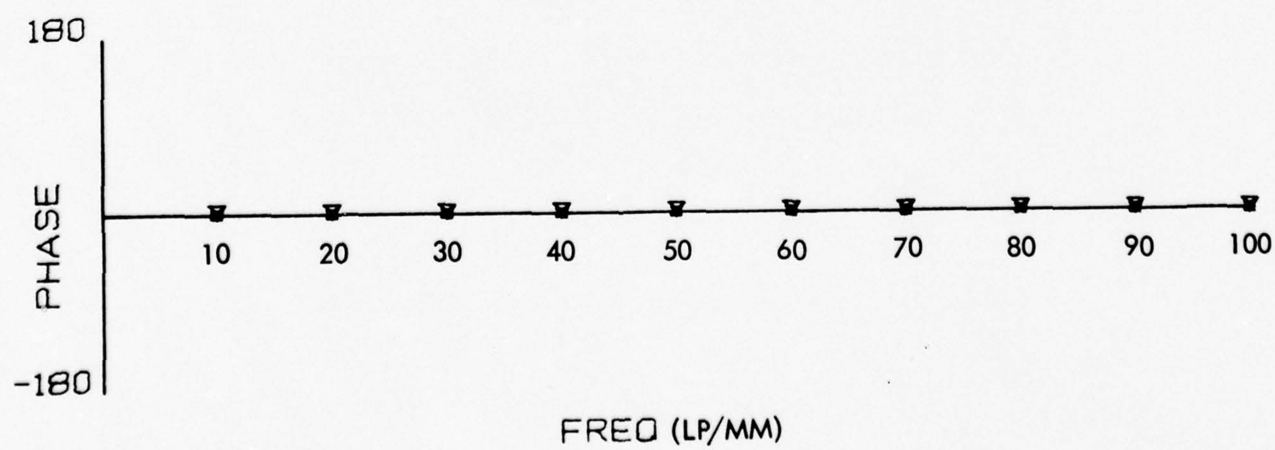


Figure 7. 18-mm AN/PVS-5 goggle objective lens--on-axis MTF plot

SYSTEM DATA

P LIGHT = 706.5 NM   S LIGHT = 546.1 NM   T LIGHT = 862.1 NM

BKFC =	10.911810	H =	-0.3600000E 09	REN =	10.000000	UK =	-0.375393	Y1 =	10.000000
FCLN =	26.638689	MAG =	-0.000000	REX =	12.419347	UKBAR=	0.289370	Y1BAR=	-4.685816
FNUM =	1.331934	OBJD =	0.1000000E 10	TEN =	13.016156	U0 =	0.000000		
GSHT =	9.596469	OVLN =	51.511810	TEX =	-22.159770	U0BAR=	0.360000		

SPHR =	-0.0190762	COMA =	-0.0219797	TANG =	0.0190158	SAGT =	-0.1253263	PETZ =	-0.1978974	DIST =	-0.0691872
SPHR5=	0.0208421	COMA5=	0.0827456	TANG5=	0.0009364	SAGT5=	0.0858284	PETZ5=	0.1072765	DIST5=	-0.0040745
SPHR7=	-0.0015191	ECOMA=	0.0446846	TOPSA=	0.1217349	SOPSA=	0.0887384				
		FA =	-0.0365312	PL =	-0.0046633	SA =	-0.0141269	SL =	0.0013041		

FULL FIELD CHIEF RAY DATA

FAN IS AT 1.00 FIELD, OBJECT HEIGHT IS -0.3600000E 09

-- CHIEF RAY DATA IN P-LIGHT --	YEN	YEX	Y-IMAGE	L/M-IMAGE
	0.000000	1.192781	8.887465	0.232679

S-T COLOR	S-P COLOR	X(S)	X(T)
-0.015171	-0.005605	-0.089523	0.026399

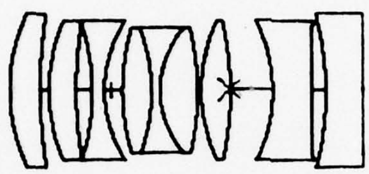
ON-AXIS MTF DATA

GOOD SPOTS P	S	T	FAILURES P	S	T	FIELD POSITION YO/H	XO/H	CHIEF RAY (IMAGE) YK	XK
40	22	22	0	0	0	0.000000	0.000000	0.000000	0.000000

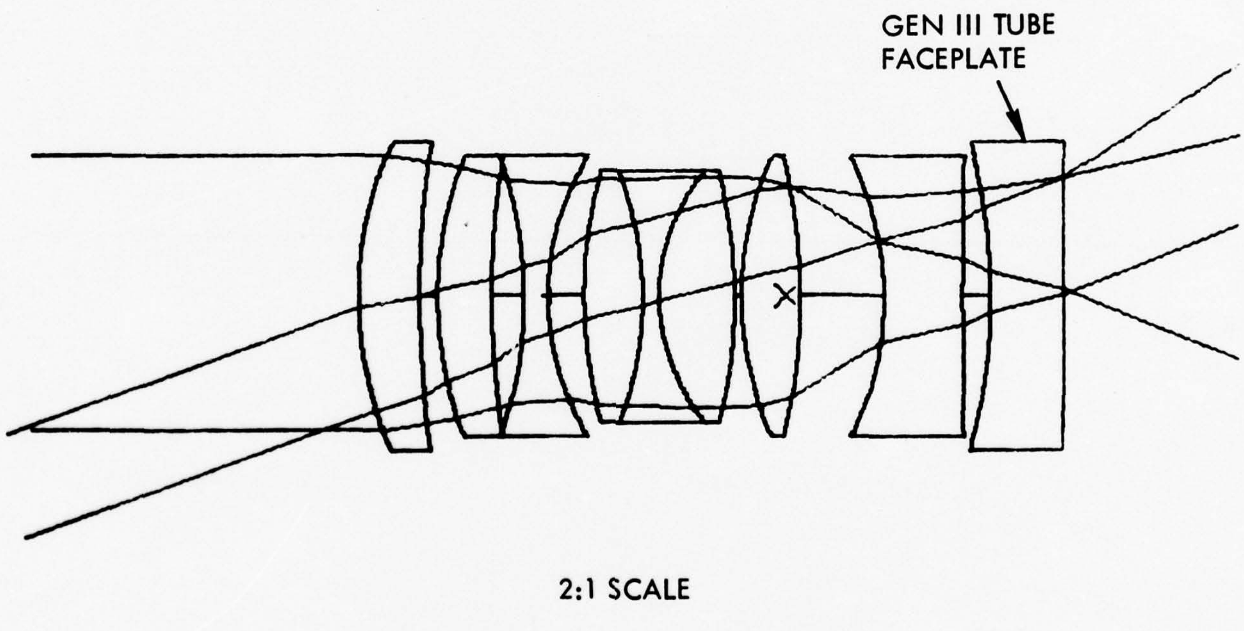
(XK,YK FOCUS-SHIFTED)

	FREQUENCY	SAGITTAL	PHASE	TANGENTIAL	PHASE	45 DEGREE	PHASE
1.	10.00000	0.930604	0.000000	0.930604	-0.000000	0.931337	-0.000000
2.	20.00000	0.767038	0.000000	0.767038	-0.000002	0.779825	-0.000002
3.	30.00000	0.603778	0.000000	0.603778	-0.000006	0.623026	-0.000006
4.	40.00000	0.506327	0.000000	0.506327	-0.000009	0.493093	-0.000008
5.	50.00000	0.469155	0.000000	0.469155	-0.000008	0.398601	-0.000005
6.	60.00000	0.444198	0.000000	0.444198	-0.000002	0.364705	0.000005
7.	70.00000	0.400428	0.000000	0.400428	0.000003	0.378599	0.000012
8.	80.00000	0.349824	0.000000	0.349824	0.000001	0.380377	0.000008
9.	90.00000	0.320104	0.000000	0.320104	-0.000009	0.350587	-0.000007
10.	100.00000	0.314453	0.000000	0.314453	-0.000023	0.331266	-0.000029

Figure 8. 18-mm AN/PVS-5 goggle objective lens--system calculations



1:1 SCALE



2:1 SCALE

Focal length	26.58 mm (λ = 800 nm)
F/no.	1.35
Field of view	40°

Figure 9. Partial modification of AN/PVS-5 with GEN III tube faceplate

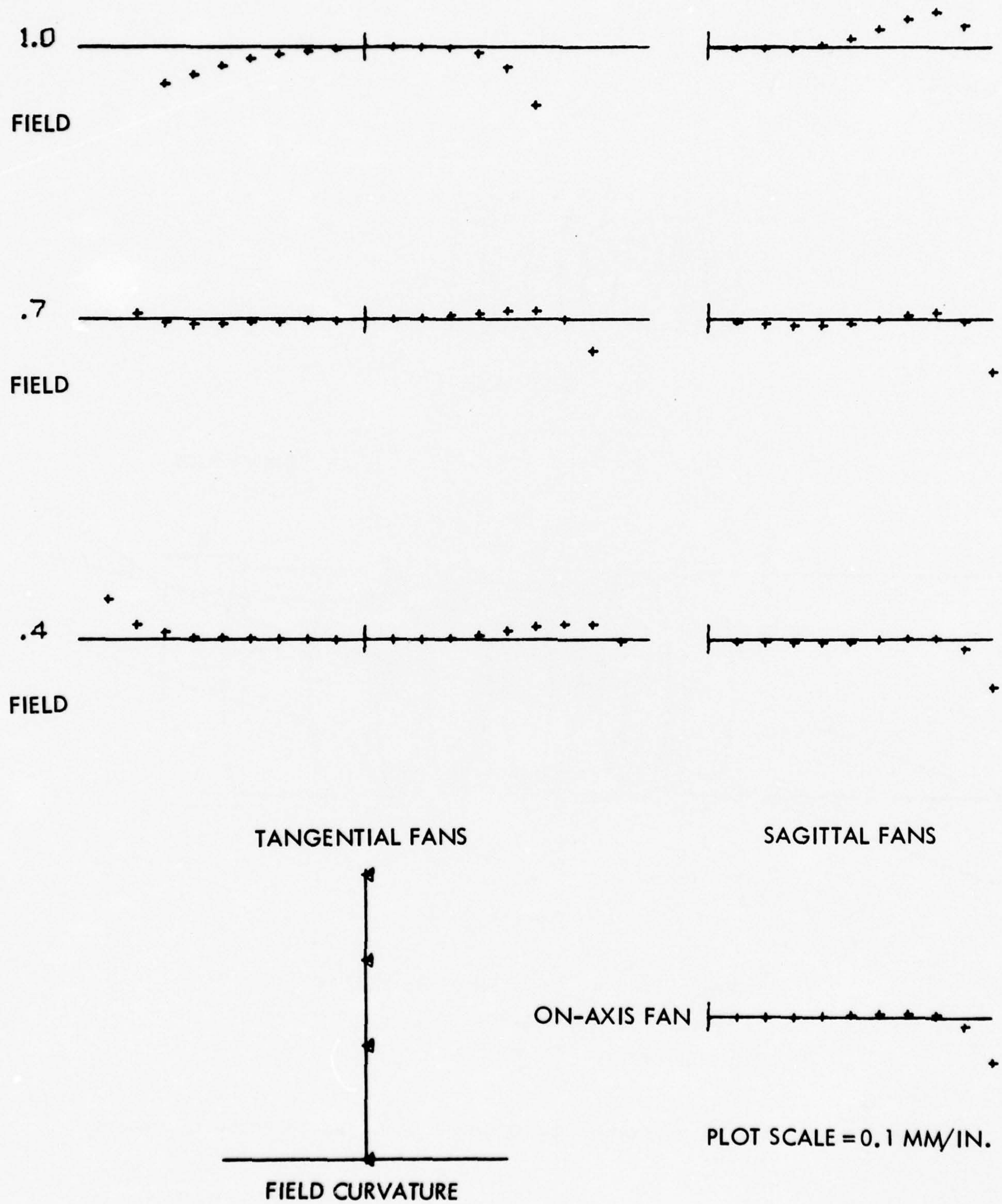


Figure 10. Partial modification of AN/PVS-5 with GEN III tube faceplate--ray trace fan plots in P light (800 nm)

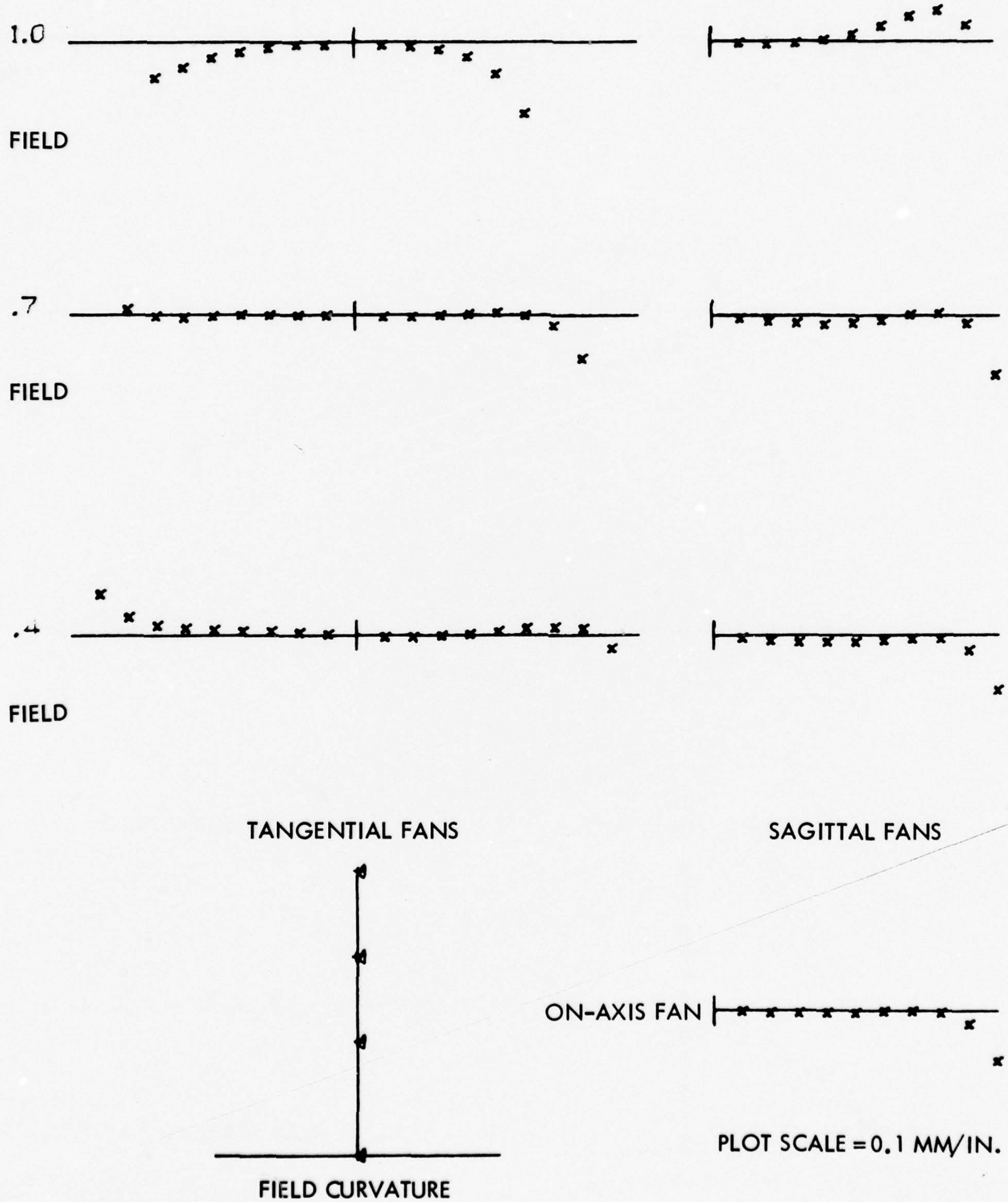


Figure 11. Partial modification of AN/PVS-5 with GEN III tube faceplate--ray trace fan plots in S light (700 nm)

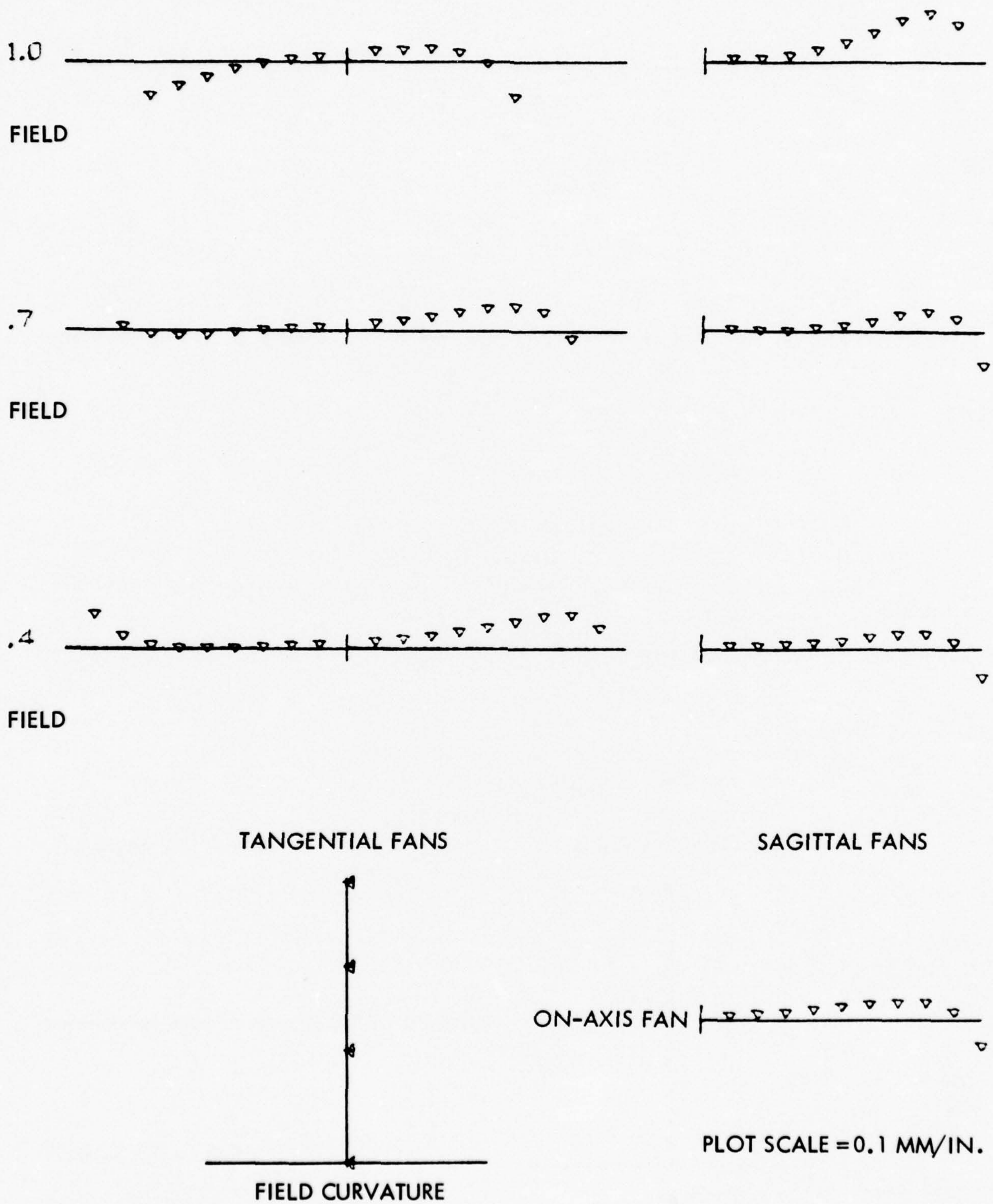
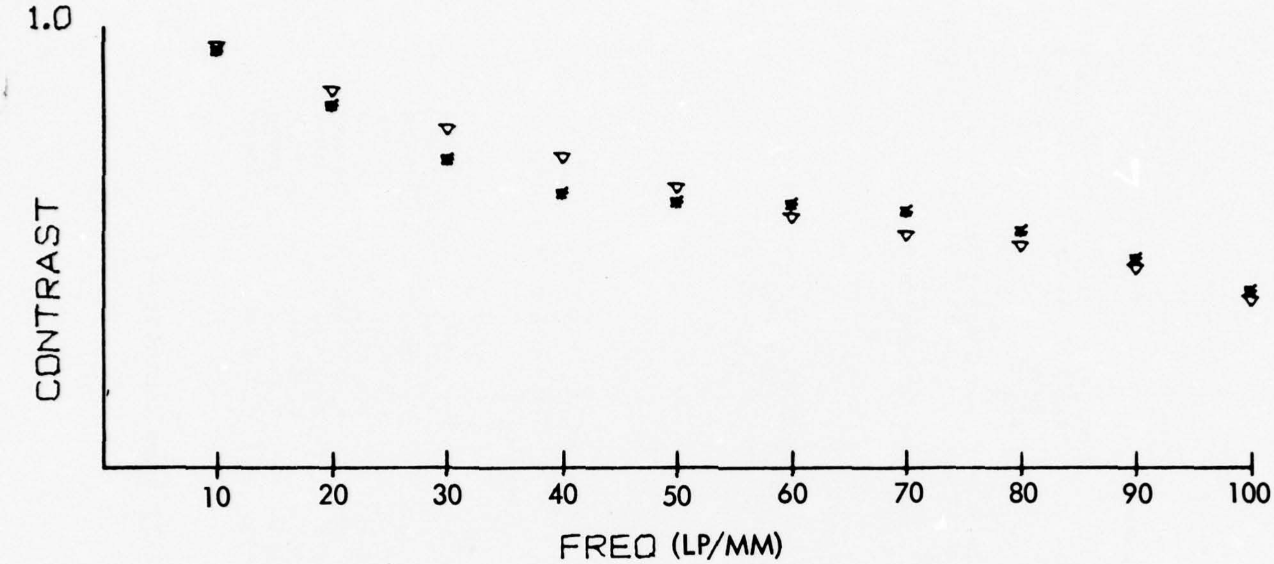


Figure 12. Partial modification of AN/PVS-5 with GEN III tube faceplate--ray trace fan plots in T light (900 nm)



		WAVELENGTH (NM)	MTF WEIGHTING
x	TANGENTIAL RESPONSE	800	40
+	SAGITTAL RESPONSE	700	8
∇	45° RESPONSE	900	8

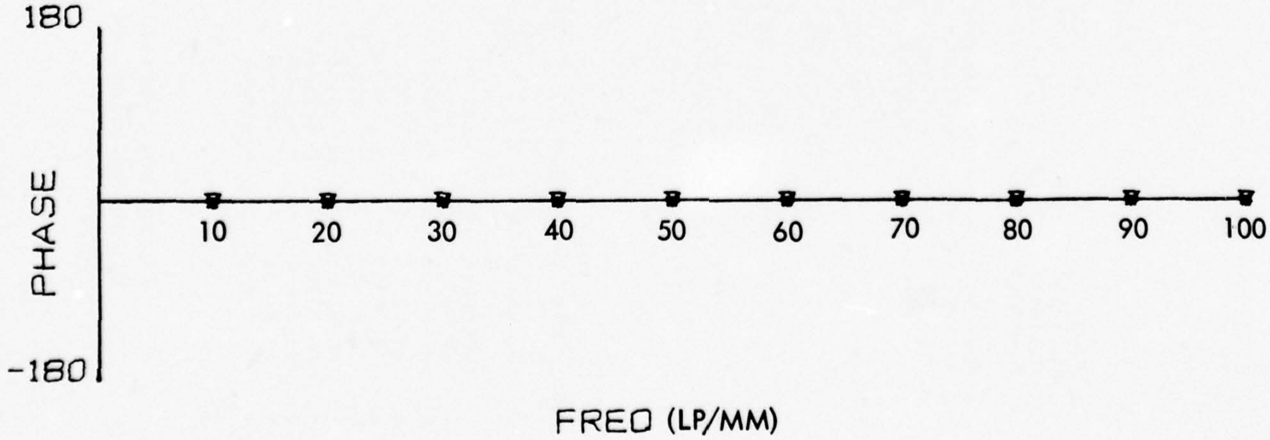


Figure 13. Partial modification of AN/PVS-5 with GEN III tube faceplate--on-axis MTF plots

SYSTEM DATA

P LIGHT = 800 NM   S LIGHT = 700 NM   T LIGHT = 900 NM

BKFC =	0.000001	H =	-0.9611038E 10	EFL =	9.378012	UK =	-0.371659	Y1 =	9.878012
FCLN =	26.578100	MAG =	-0.000000	EFX =	7.729809	UKBAR=	0.460048	Y1BAR=	-4.686411
FNUM =	1.345316	OBJD =	0.2669733E 11	TFL =	13.017809	U0 =	0.000000		
GSHT =	9.567968	OVLN =	50.872159	TFX =	-20.797754	U0BAR=	0.360000		

SPHR =	0.0167751	COMA =	0.0405832	TANG =	-0.0044849	SAGT =	-0.0688470	PETZ =	-0.1010281	DIST =	-0.0697800
SPHR5=	-0.0000017	COMA5=	0.0249715	TANG5=	0.0407697	SAGT5=	0.0652853	PETZ5=	0.0714143	DIST5=	-0.0010920
SPHR7=	-0.0162611	ECOMA=	-0.0439639	TOBSA=	0.0469938	SOBSA=	0.0792641				
		PA =	-0.0179905	PL =	-0.0035152	SA =	-0.0073476	SL =	-0.0010104		

FULL FIELD CHIEF RAY DATA

FAN IS AT 1.00 FIELD, OBJECT HEIGHT IS -0.9611039E 10

-- CHIEF RAY DATA IN P-LIGHT --

YEN	YEX	Y-IMAGE	L/M-IMAGE
0.000000	0.200236	8.893130	0.417972

S-T COLOR	S-P COLOR	X(S)	X(T)
-0.005728	-0.002144	-0.019552	0.015991

ON-AXIS MTF DATA

GOOD SPOTS			FAILURES			FIELD POSITION		CHIEF RAY (IMAGE)		
P	S	T	P	S	T	YO/H	XO/H	YK	XK	(XK,YK FOCUS-SHIFTED)
40	8	8	0	0	0	0.000000	0.000000	0.000000	0.000000	

	FREQUENCY	SAGITTAL	PHASE	TANGENTIAL	PHASE	45 DEGREE	PHASE
1.	10.00000	0.949242	0.000000	0.949242	-0.000003	0.951127	-0.000002
2.	20.00000	0.827352	0.000000	0.827352	-0.000009	0.849147	-0.000005
3.	30.00000	0.701580	0.000000	0.701579	-0.000016	0.762980	-0.000009
4.	40.00000	0.625331	0.000000	0.625331	-0.000023	0.699262	-0.000014
5.	50.00000	0.604036	0.000000	0.604036	-0.000025	0.629235	-0.000018
6.	60.00000	0.603332	0.000000	0.603332	-0.000023	0.561036	-0.000022
7.	70.00000	0.585896	0.000000	0.585896	-0.000017	0.522628	-0.000024
8.	80.00000	0.540055	0.000000	0.540055	-0.000009	0.498048	-0.000025
9.	90.00000	0.476977	0.000000	0.476977	-0.000003	0.446446	-0.000026
10.	100.00000	0.407408	0.000000	0.407407	-0.000001	0.373158	-0.000029

Figure 14. Partial modification of AN/PVS-5 with GEN III tube faceplate--system calculations

The triplet elements (4A, 4B, and 4C), plus the last two elements (5 and 6), are modified in position, shape, and thickness to control the aberration balance between surfaces 12 and 13 for correction of the faceplate aberrations. Elements 1, 2, and 3, and their intermediate spacings are held unchanged. The image intensifier tube faceplate has a spherical curvature with a radius of 44.3 mm. One glass change is present in element 6. The replacement is a flint glass of higher index and dispersion than the original.

The on-axis results show some improvement over the GEN II objective. Though higher order spherical aberrations are apparent in the outermost rays (note negative curl of the on-axis fan plots), MTF calculations show a 6 percent gain in contrast at both 20 and 40 line pairs per millimeter. The presence of the higher order effects impose the f/1.35 speed of this system as a maximum. If the aperture is opened, the minimum attainable on-axis spot size increases and a consequent reduction in contrast occurs.

Imaging off-axis is nearly equivalent to that of the GEN II objective. A different type of aberration balance exists with some residual negative higher order coma at full field. The resolution at these field angles can be improved by vignetting. This is an area for trade-off analysis. In many available binocular systems, high relative illuminance levels are not provided at full field and have proven not to be necessary. Since an observer tends to concentrate on the center of the field of view, and the option of adjusting the subject matter in this field exists, vignetting is not detrimental when the outer parts are visible for reference. The amount of vignetting necessary to improve the off-axis imaging will reduce the percent relative illuminance to approximately 50 percent from an initial 70 percent. Such a reduction is not significant.

Distortion is determined from the equation:

$$\% \text{ distortion} = \frac{\text{GSHT} - \text{Y-image}}{\text{GSHT}} \times 100\%$$

Y-image, the exact image height calculated by ray tracing, is provided under the heading "Full Field Chief Ray Results" on the system calculations page (Figure 14). GSHT, located under "System Data" on the same page, is the gaussian or first order approximation of the image height. This system's distortion of -7.1 percent closely matches the -7.3 percent of the original objective, providing compatibility with the current goggle eyepiece.

The length of the barrel assembly for this lens will be approximately 46 mm and have a glass weight close to 49 grams. (Note: GEN III lens lengths do not include the faceplate thickness.) Installation of a diaphragm iris, for reduction of aperture at higher than normal light levels and for increased depth of field, should be positioned behind the third lens element. The lens spacing is not, however, sufficient to easily retain the adjacent lenses and simultaneously mount the adjustable iris.

All surface curvatures and element combinations result in a manufacturing cost comparable to that of the AN/PVS-5 system. The edge on element 5 (1 mm at 20.2-mm diameter) indicates that a special lens cell must be used to mount this element if a single bore lens barrel is to be used. Further study and greater modification could alleviate this problem. Tube manufacturing costs may increase due to the curved surface required on the intensifier tube faceplate. This surface must be controlled in figure, centering, and sag to the same tight tolerances imposed on high quality lens elements.

2.3 TASK 2

2.3.1 Full Modification of AN/PVS-5 Goggle Objective With Thick Faceplate (Figures 15 Through 20)

The lens configuration of the AN/PVS-5 does not lend itself to extensive changes in element glass types without significant changes in the total lens configuration. Two advantageous material changes, plus controlled adjustment of the aberration balance, permit a reasonable performance result while maintaining a flat faceplate.

All curvatures, thicknesses, and airspaces are changed from the GEN II configuration. Element 4B (center of the triplet) is now a recently developed lightweight flint of higher index and dispersion than the original glass. Because element 6 contributes the same overcorrected spherical and axial color as the faceplate, this element's effect in these areas is reduced by using a lower index flint with less dispersion.

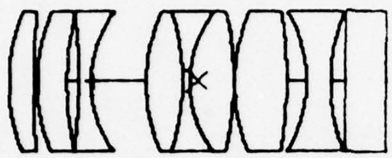
A better balance of higher order spherical aberrations with the third order contribution establishes an on-axis MTF higher than that of both the GEN II objective and the previously discussed partial modification. Gains of 14 percent for 20 lp/mm and 20 percent for 40 lp/mm at f/1.3 are achieved over the AN/PVS-5. This speed is a maximum, as the dominance of higher order aberrations is already evident (see on-axis fan plots, Figures 16 through 18).

Similar improvements are present off-axis as the negative coma of the faceplate is neutralized. Calculation of distortion from the full field chief ray results gives -7.1 percent, again compatible with the current eyepiece. The sagittal full field fan does demonstrate some residual oblique spherical aberration, but, in general, the performance is equal to or better than that of the AN/PVS-5.

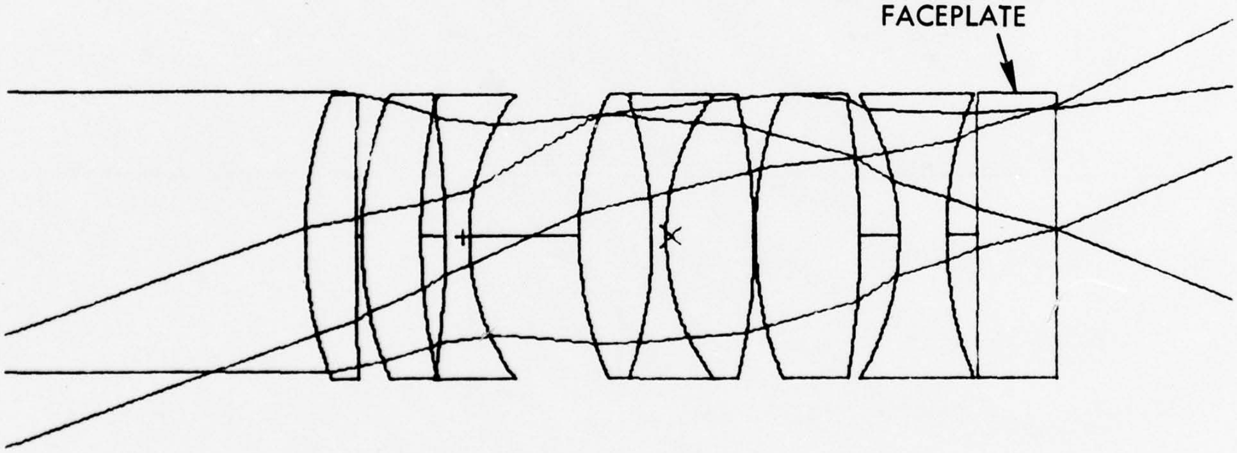
Figure 15 demonstrates that a single barrel inner diameter may be used for mounting the lens. The length of the barrel will be approximately 49 mm, which is longer than the partial modification, but not excessive. The natural stop is at element 3. The airspace between this element and the next is better suited for mounting an iris diaphragm than that afforded by the partial modification. An estimated glass weight for this system is 51 grams.

The MTF and aberration data show that when scaled for a 12-mm format, this design might be opened up to f/1.2. If further study allows modification of the higher order spherical aberration, a speed of f/1.1 might be possible. The 51 grams listed above would scale to approximately 16 grams, but this number would increase if the f/number is opened up.

Several inherent characteristics of the AN/PVS-5 goggle objective still present in this system prevent significant reduction of weight and manufacturing costs. Several glass types are premium in quality with excellent resistance to environment, high transformation temperatures (desirable in obtaining hard coatings), and reasonable staining resistance. Unfortunately, weight and cost suffer. Over 50 percent of the glass types in the AN/PVS-5 have densities exceeding 4.00 g/cm^3. In addition, four of the elements have glass prices over $50.00 per pound (grade A slab price). The lightweight, inexpensive replacement glasses used in this full modification cannot produce a noticeable reduction in weight and cost with these factors--plus the complex lens configuration--to overcome.



1:1 SCALE



2:1 SCALE

Focal length	26.55 mm (λ = 800 nm)
F/no.	1.30
Field of view	40°

Figure 15. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate

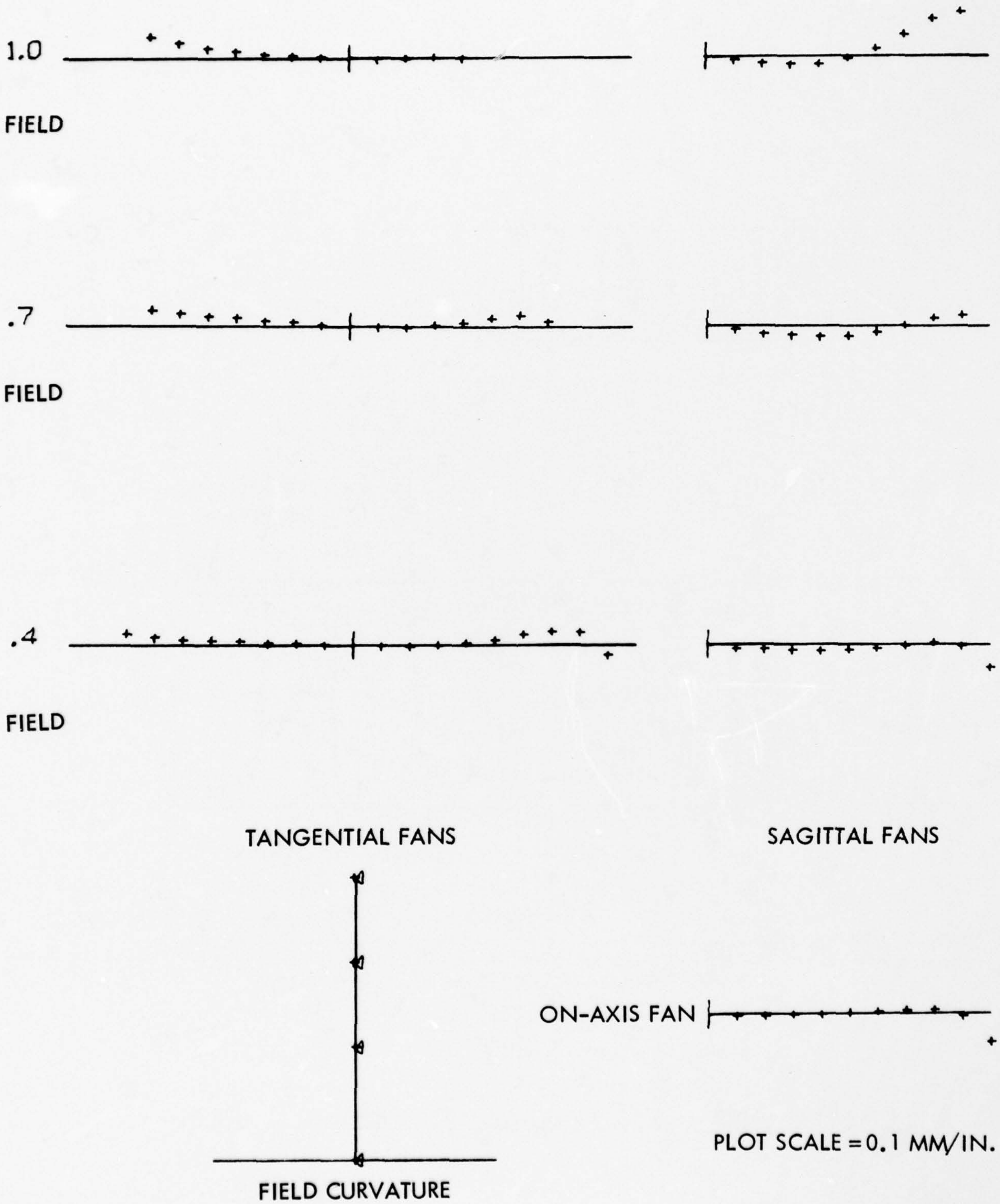


Figure 16. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for P light (800 nm)

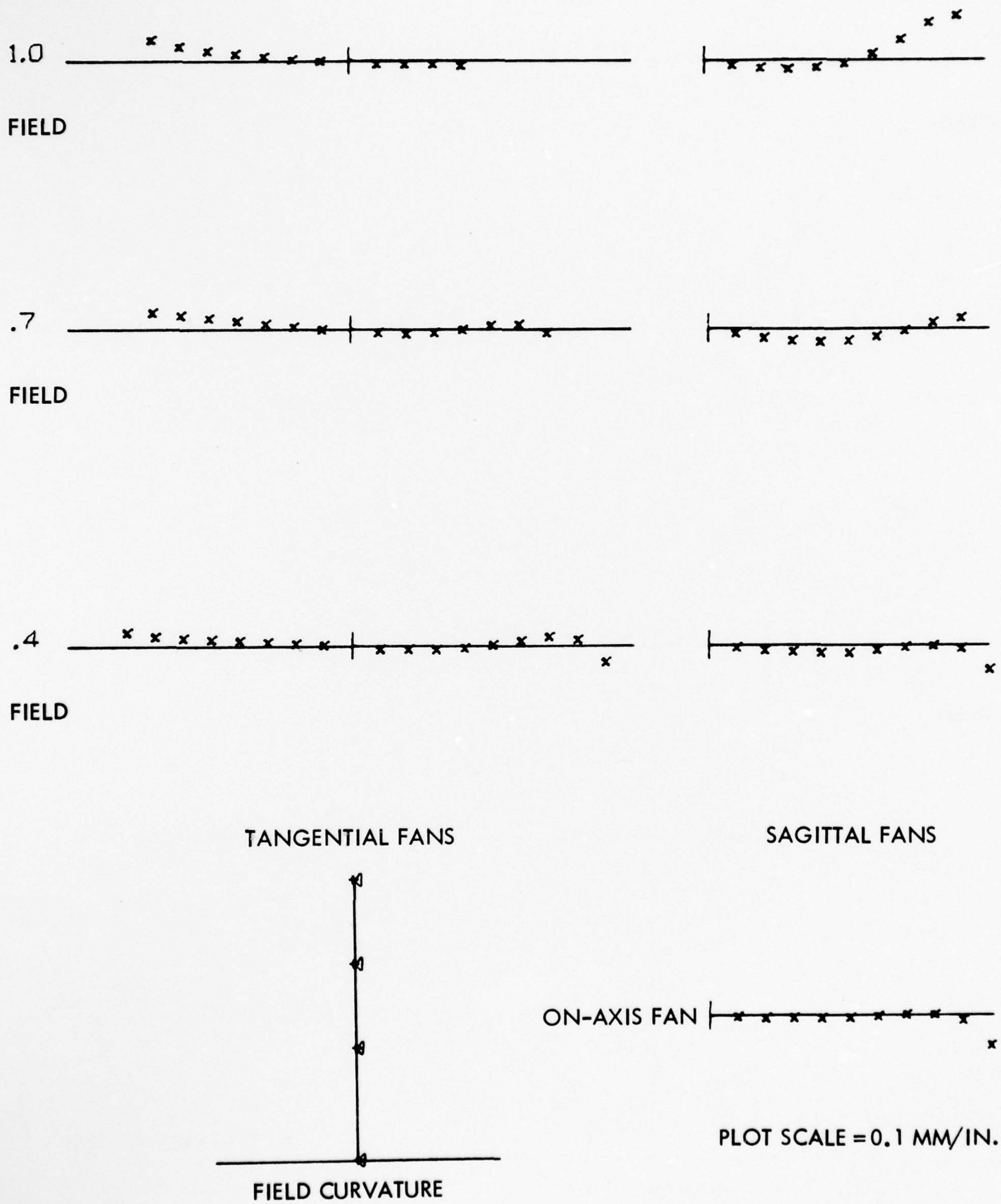


Figure 17. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for S light (700 nm)

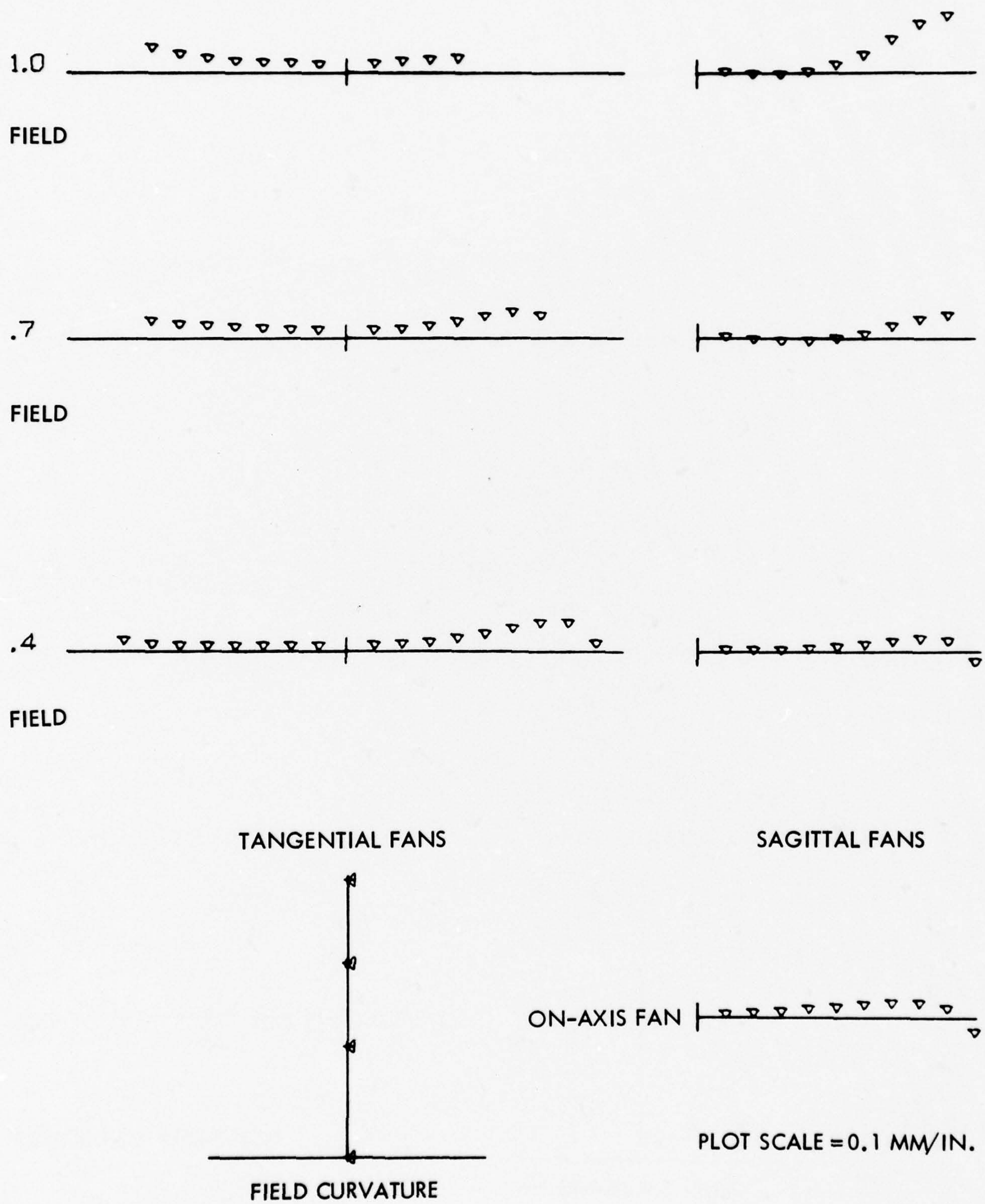
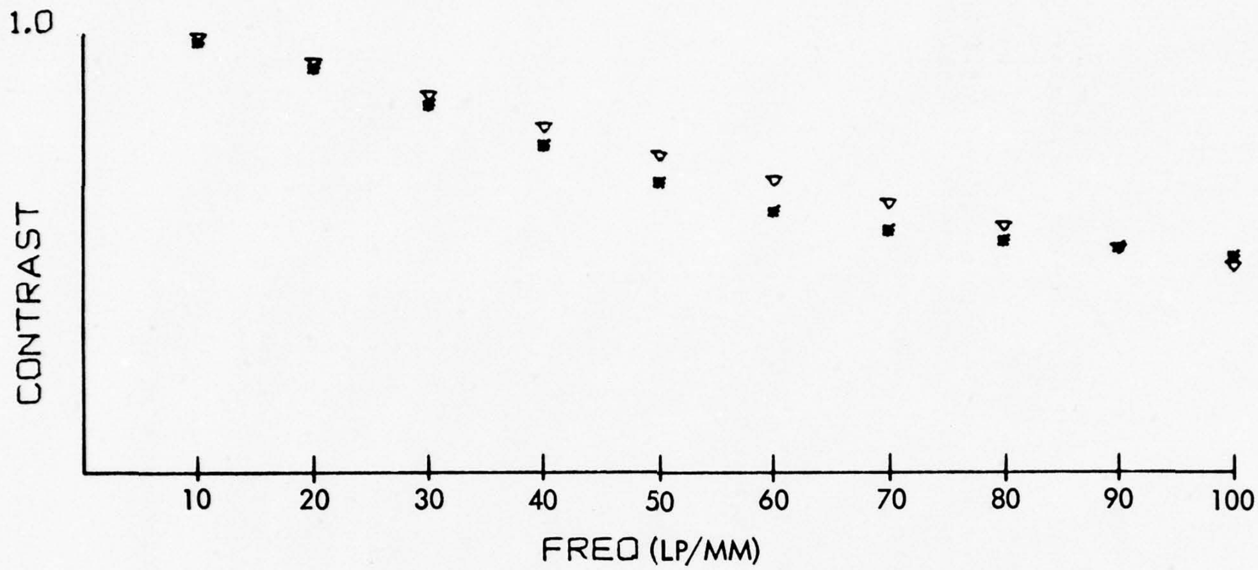


Figure 18. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for T light (900 nm)



		WAVELENGTH (NM)	MTF WEIGHTING
×	TANGENTIAL RESPONSE	800	40
+	SAGITTAL RESPONSE	700	8
∇	45° RESPONSE	900	8

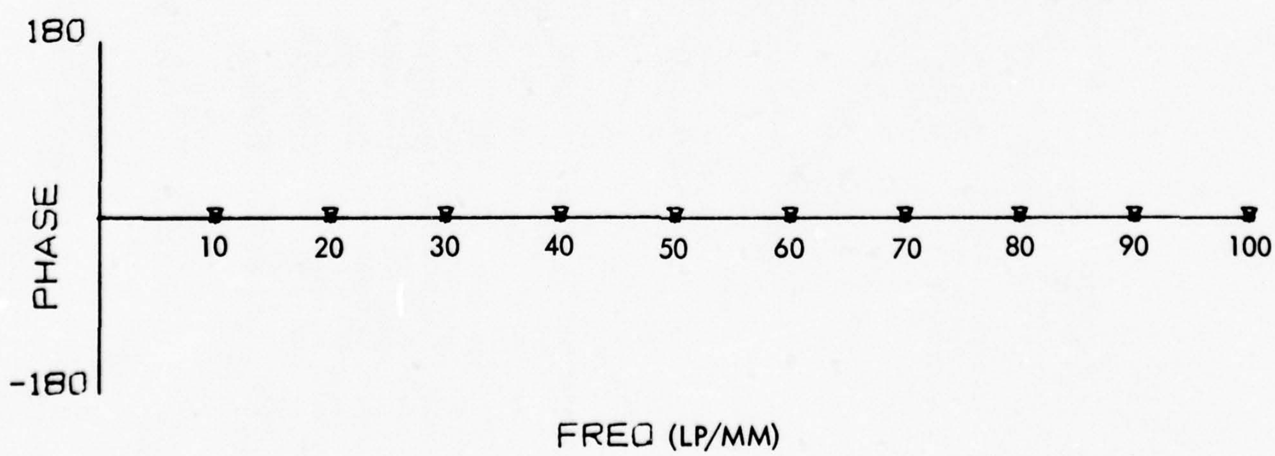


Figure 19. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--on-axis MTF plots

SYSTEM DATA

P LIGHT = 800 NM   S LIGHT = 700 NM   T LIGHT = 900 NM

BKFC =	0.000001	H =	-0.9499017E 10	REN =	10.211440	UK =	-0.384600	Y1 =	10.211440
FCLN =	26.550750	MAG =	-0.000000	REX =	10.963174	UKBAR=	0.335315	Y1BAR=	-3.802594
FNUM =	1.300049	OBJD =	0.2638616E 11	TEN =	10.562763	U0 =	0.000000		
GSHT =	9.558936	OVLN =	54.114535	TEX =	-28.507319	U0BAR=	0.360000		

SPHR =	0.0169527	COMA =	0.0250730	TANG =	-0.0292960	SAGT =	-0.0858941	PETZ =	-0.1141932	DIST =	-0.0703887
SPHR5=	0.0000308	COMA5=	0.0485097	TANG5=	0.0330911	SAGT5=	0.0607788	PETZ5=	0.0677008	DIST5=	-0.0006153
SPHR7=	-0.0122014	ECOMA=	0.0222658	TOBSA=	0.0775452	SOBSA=	0.0949517				
		PA =	-0.0152737	PL =	-0.0071754	SA =	-0.0065146	SL =	-0.0027252		

FULL FIELD CHIEF RAY DATA

FAN IS AT 1.00 FIELD, OBJECT HEIGHT IS -0.9499017E 10

-- CHIEF RAY DATA IN P-LIGHT --	YEN	YEX	Y-IMAGE	L/M-IMAGE
	0.000000	0.789913	8.895508	0.283986

S-T COLOR	S-P COLOR	X(S)	X(T)
-0.005901	-0.001871	-0.068009	-0.007977

ON-AXIS MTF DATA

GOOD SPOTS P	S	T	FAILURES P	S	T	FIELD POSITION YO/H	XO/H	CHIEF RAY (IMAGE) YK	XK (XK,YK FOCUS-SHIFTED)
40	8	8	0	0	0	0.000000	0.000000	0.000000	0.000000

	FREQUENCY	SAGITTAL	PHASE	TANGENTIAL	PHASE	45 DEGREE	PHASE
1.	10.00000	0.978367	0.000000	0.978367	-0.000007	0.978606	-0.000005
2.	20.00000	0.918399	0.000000	0.918399	-0.000015	0.921774	-0.000010
3.	30.00000	0.833339	0.000000	0.833339	-0.000022	0.847203	-0.000016
4.	40.00000	0.740659	0.000000	0.740659	-0.000030	0.772951	-0.000022
5.	50.00000	0.656825	0.000000	0.656825	-0.000036	0.708511	-0.000028
6.	60.00000	0.592681	0.000000	0.592681	-0.000041	0.653066	-0.000035
7.	70.00000	0.550960	0.000000	0.550959	-0.000045	0.600659	-0.000043
8.	80.00000	0.526618	0.000000	0.526618	-0.000048	0.548085	-0.000052
9.	90.00000	0.509710	0.000000	0.509710	-0.000050	0.498741	-0.000062
10.	100.00000	0.489605	0.000000	0.489604	-0.000053	0.459677	-0.000072

Figure 20. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--system calculations

2.3.2 Coupling of Baird-Atomic Lens No. MT/RR-001 to Thick Faceplate (Figures 21 Through 26)

As stated in the discussion of Task 1, the thick faceplate introduces over-corrected spherical and axial color, with off-axis positive astigmatism and negative coma. The new design reported in this section compensates for several of these problems and demonstrates the potential for modification toward an overall high quality performance.

The Baird-Atomic objective lens (No. MT/RR-001) consists of four simple singlets plus a doublet, and contains only two optical materials. Elements 1, 3, and 4B are of readily available, inexpensive, low dispersion crown glass. A styrene plastic is used in the remainder of the elements as a flint. Aspheric surfaces are not used on the plastic elements, but can be introduced to obtain increased performance levels.

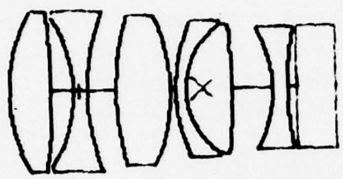
The length of the barrel assembly for this lens is 42 mm, a substantial improvement over that of the AN/PVS-5 by virtue of a 10-mm reduction. With no thin edge problems, a uniform barrel inner diameter is easily accommodated. However, the natural stop position, located after element 2, implies some difficulty in mounting an iris diaphragm. The glass/plastic weight is 28.3 grams, far lower than in any of the other systems considered, with the density of styrene (1.04 grams/cm^3) accounting for much of this weight-saving.

The on-axis fan plots and MTF demonstrate excellent balancing of axial aberrations. Contrast is held to greater than 58 percent as far as 100 lp/mm, with values of 94 percent at 20 lp/mm, and 83 percent at 40 lp/mm. Because of the resolution limit of image intensifier tubes, this MTF is excessive and should be reduced to permit improvement in the off-axis behavior. Such a reduction will not result in a significant decrease in the f/1.25 speed, as trade-off can be accomplished without decreasing the system aperture.

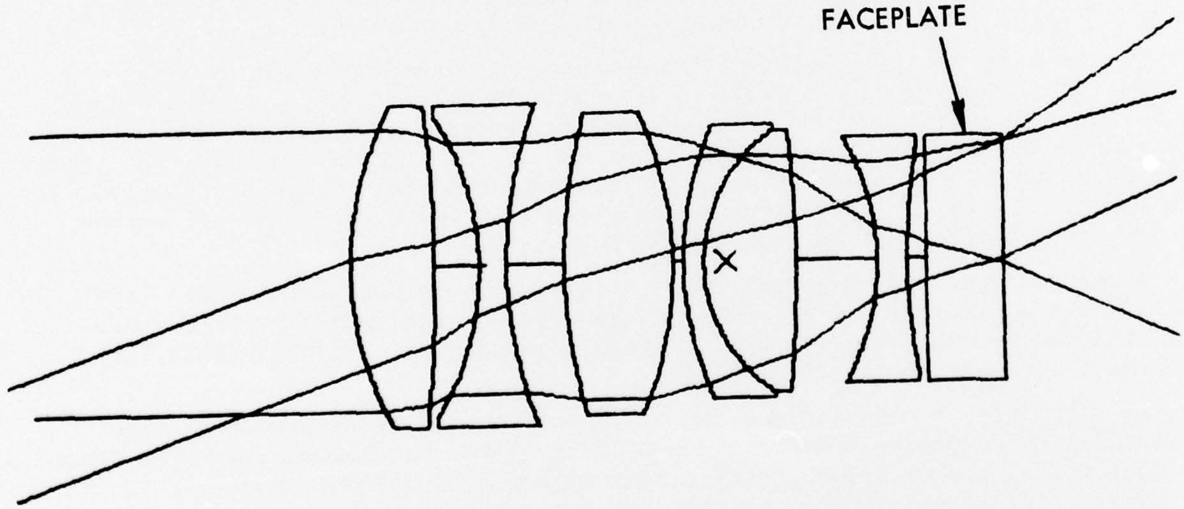
A final version of this lens could attain a speed approaching f/1.0 when scaled to a 12-mm format. In addition, the glass weight would most likely be less than 10 grams. Optimization of overall image quality for an 18-mm format ensures a similar result when scaled.

As presented, the design does not fully compensate at intermediate field angles for the negative coma introduced by the thick faceplate of GEN III tubes. At full field, higher order positive aberrations overcome the coma, but residual oblique spherical aberration remains. In optimizing the off-axis resolution, the distortion will also have to be modified as it is currently -4.9 percent.

Because of the small size of goggle objective elements, the material cost of the glasses is not as significant as their workability. This lens design is extremely simple in this respect. The glass elements are easily manufactured lens shapes, and the plastic elements, on a production basis, could be from 1/2 to as little as 1/20th the cost of equivalent glass elements. The exact cost of the plastics is a function of the production quantity, precision requirements, and optical coating complications. Due to the simplicity of this lens configuration, cost savings will still be evident even if replacement glass elements are used. If the benefits of plastics in cost and weight are to be realized, the current goggle standards may have to be relaxed. Plastics are not as stable as desired, which limits their use in systems containing critical balancing of surface aberrations.



1:1 SCALE



2:1 SCALE

Focal length	26.24 mm (λ = 800 nm)
F/no.	1.25
Field of view	40°

Figure 21. MT/RR-001 objective lens with GEN III tube faceplate

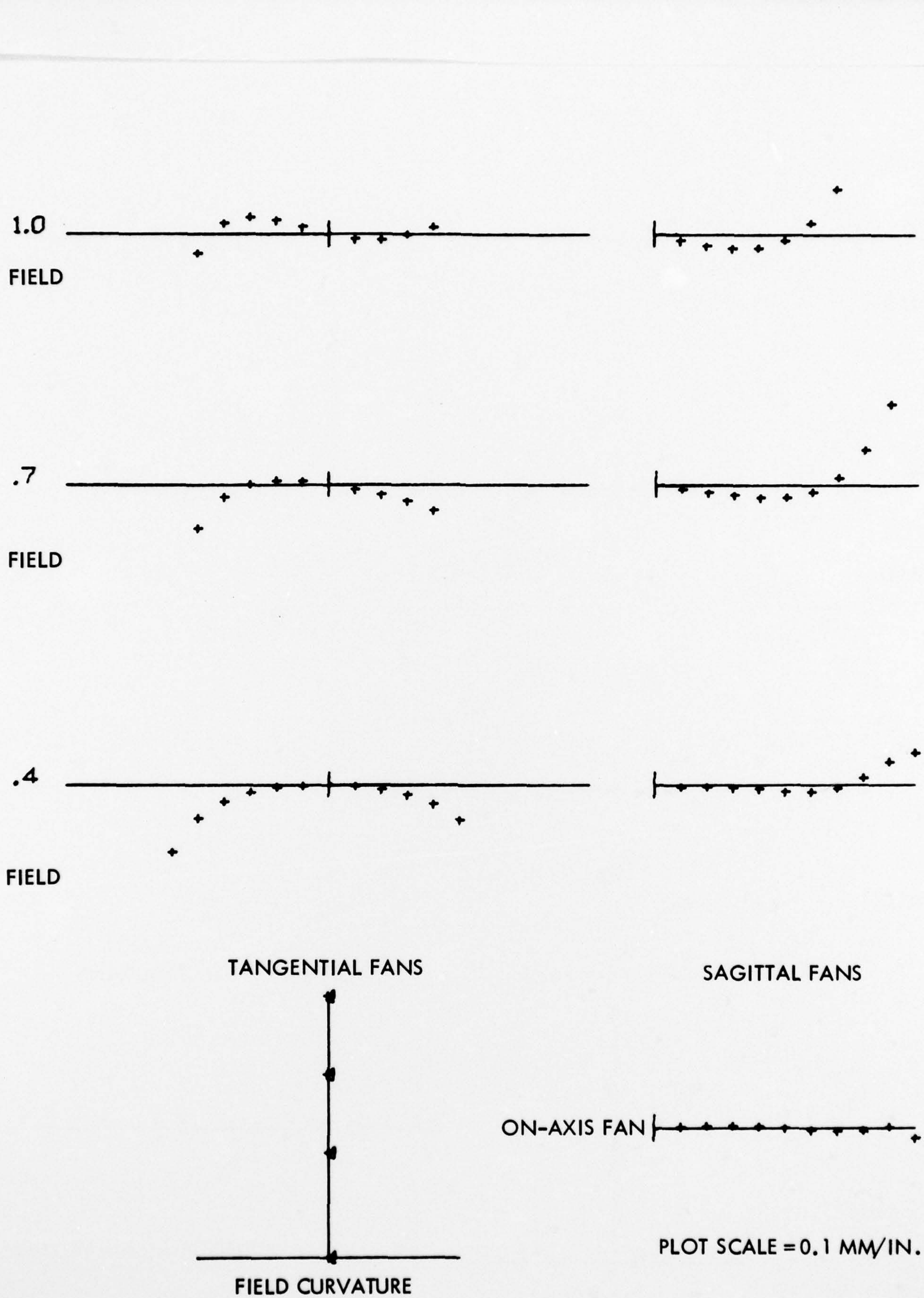


Figure 22. *MT/RR-001 objective lens with GEN III tube faceplate--ray trace fan plots for P light (800 nm)*

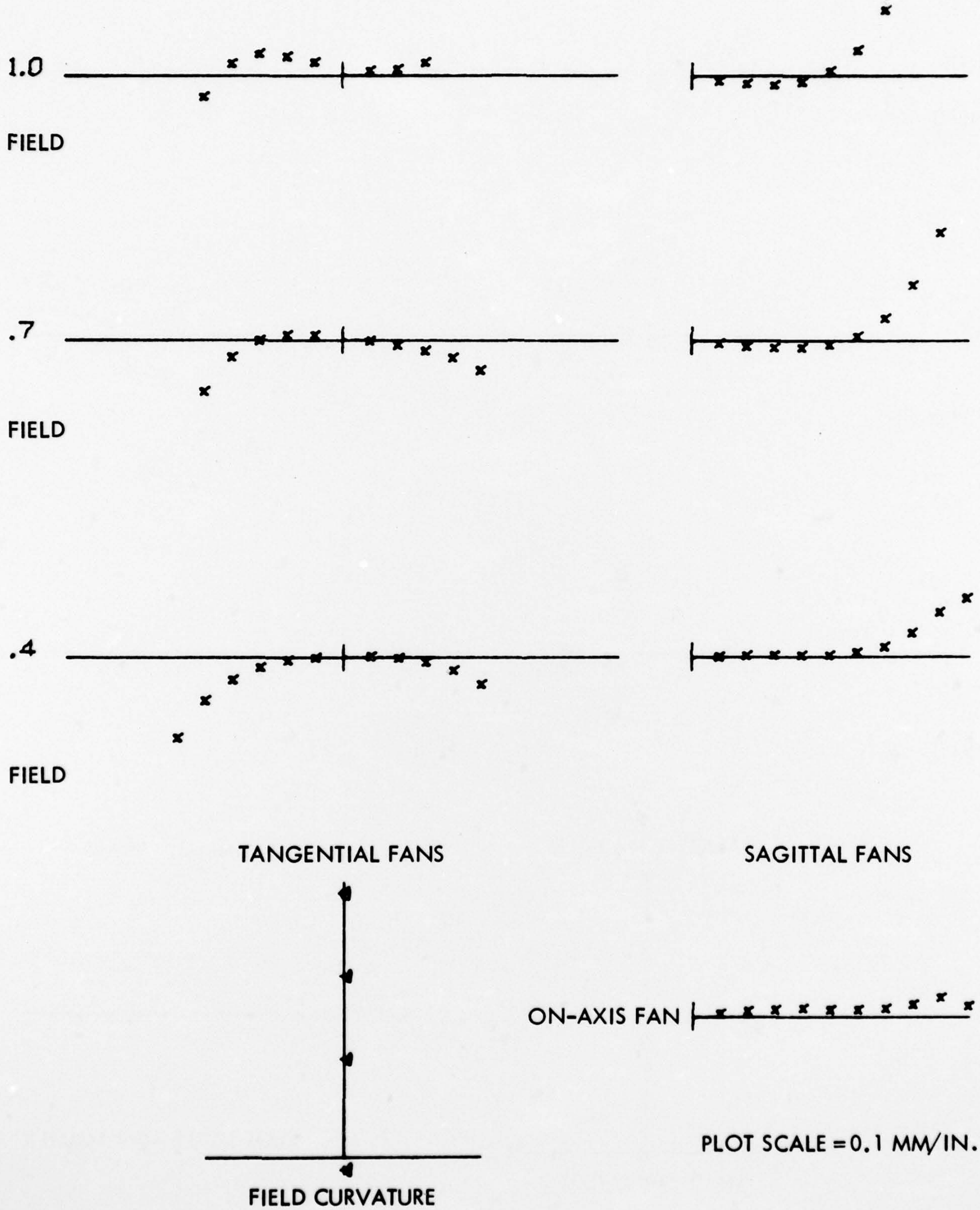


Figure 23. MT/RR-001 objective lens with GEN III tube faceplate--ray trace fan plots for S light (700 nm)

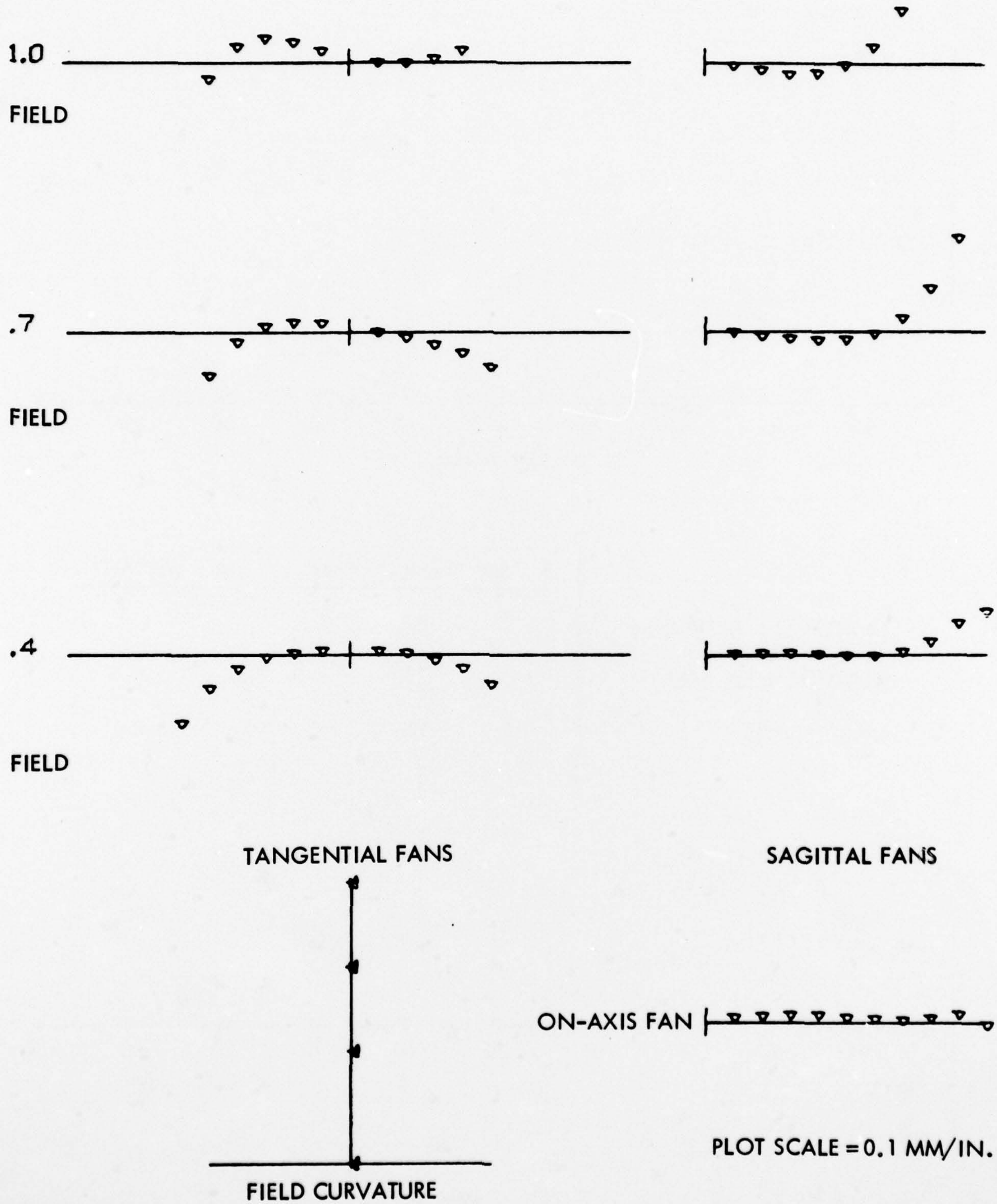


Figure 24. MT/RR-001 objective lens with GEN III tube faceplate--ray trace fan plots for T light (900 nm)

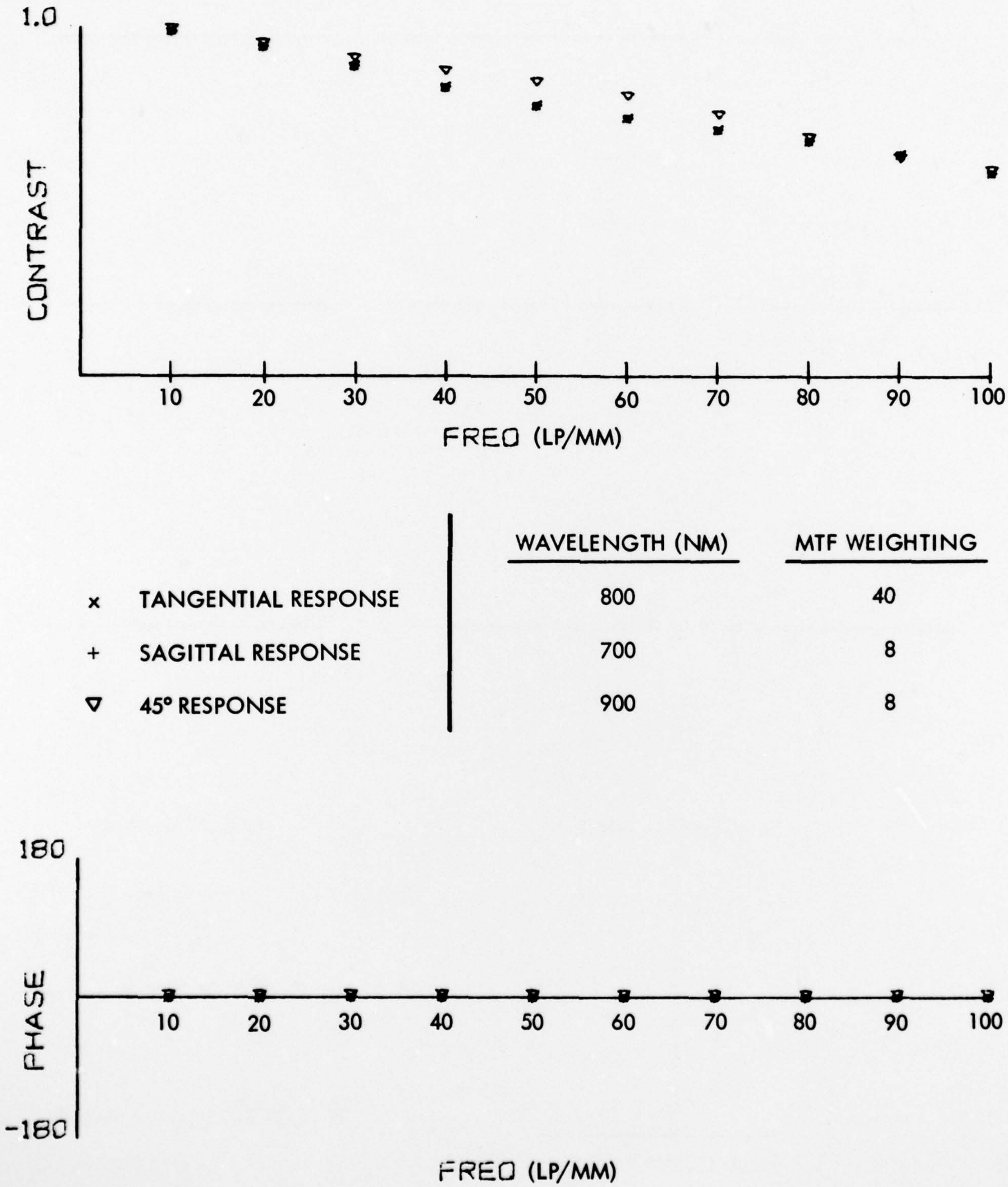


Figure 25. MT/RR-001 objective lens with GEN III tube faceplate--on-axis MTF plots

SYSTEM DATA

P LIGHT = 800 NM S LIGHT = 700 NM T LIGHT = 900 NM

```
BKFC =     0.000010   H     =-0.7055943E 10   REN  =    10.500000   UK    =   -0.400140   Y1    =   10.500000
FCLN =    26.240767   MAG   =     -0.000000   REX  =     8.351932   UKBAR=     0.452589   Y1BAR=    -3.105631
FNUM =     1.249560   OBJD  = 0.1959984E 11   TEN  =     8.626753   U0    =    0.000000
GSHT =     9.429872   OVLN  =     47.173119   TEX  =   -20.835348   U0BAR=     0.360000

SPHR =   -0.0747364 COMA =   -0.1678585 TANG =   -0.1305013 SAGT =   -0.1172795 PETZ =   -0.1106686 DIST =   -0.0481948
SPHR5=    0.0658596 COMA5=   -0.4135599 TANG5=    0.0571687 SAGT5=    0.0541446 PETZ5=    0.0533886 DIST5=   -0.0007145
SPHR7=    0.0231982 ECOMA=    0.1903245 TOBSA=    0.3761897 SOBSA=    0.1784069
                    PA   =    0.0066364 PL   =   -0.0013214 SA   =    0.0096032 SL   =    0.0013591
```

FULL FIELD CHIEF RAY DATA

```
                     FAN IS AT  1.00 FIELD, OBJECT HEIGHT IS -0.7055944E 10
-- CHIEF RAY DATA IN P-LIGHT --        YEN         YEX        Y-IMAGE    L/M-IMAGE
                                    0.000000   -0.221367    8.970542    0.441169

   S-T COLOR   S-P COLOR     X(S)        X(T)
   0.004523    0.005050   -0.102570   -0.086376
```

ON-AXIS MTF DATA

```
GOOD SPOTS    FAILURES        FIELD POSITION              CHIEF RAY (IMAGE)
 P   S   T    P   S   T       YO/H         XO/H           YK          XK   (XK,YK FOCUS-SHIFTED)
40   8   8    0   0   0       0.000000     0.000000       0.000000    0.000000
```

	FREQUENCY	SAGITTAL	PHASE	TANGENTIAL	PHASE	45 DEGREE	PHASE
1.	10.00000	0.984510	0.000000	0.984510	-0.000002	0.984840	-0.000001
2.	20.00000	0.942415	0.000000	0.942415	-0.000005	0.946907	-0.000003
3.	30.00000	0.885007	0.000000	0.885007	-0.000007	0.903007	-0.000005
4.	40.00000	0.825818	0.000000	0.825818	-0.000010	0.865026	-0.000007
5.	50.00000	0.775196	0.000000	0.775196	-0.000014	0.832001	-0.000008
6.	60.00000	0.736544	0.000000	0.736544	-0.000016	0.793146	-0.000010
7.	70.00000	0.705832	0.000000	0.705832	-0.000019	0.740193	-0.000011
8.	80.00000	0.674509	0.000000	0.674509	-0.000021	0.677356	-0.000013
9.	90.00000	0.634333	0.000000	0.634333	-0.000023	0.619692	-0.000016
10.	100.00000	0.581845	0.000000	0.581845	-0.000026	0.561522	-0.000018

Figure 26. MT/RR-001 objective lens with GEN III tube faceplate--system calculations

3. CONCLUSIONS

A summary of the evaluation results is presented in Table 1 for reference. The conclusions given below are based upon the collected data and the results obtained for this report.

- The standard 40-degree GEN II goggle objective lens will not provide an adequate image through the flat faceplate of the GEN III image tube.
- A standard 40-degree GEN II goggle objective lens, with 75 percent of its elements modified, will give an adequate image on a curved faceplate GEN III tube, but is not a reasonable solution due to the high cost associated with this special curved image tube faceplate.
- A lens using the general form factor of a GEN II lens, but with new curvatures and some low-cost glass, will offer good image quality on a flat faceplate GEN III lens.
- A lens designed solely for the narrow spectral response of a flat faceplate GEN III tube is the best solution.
- No substantial gain in optical aberration correction is achieved by curving the thick faceplate of the GEN III tube.
- The stability of plastic lens elements limits the useful operational temperature range for total aberration correction.
- The length, weight, and cost of goggle objective lens systems can only be reduced in a lens with form factors different from those of the GEN II lens design.
- A multilayer, antireflection coating on the tube may improve the contrast transfer of a GEN III tube. Because of the low index glass faceplate, single layer magnesium fluoride does not offer much improvement over uncoated glass for its cost.
- Any rejection filters needed should be built into the objective lens glass to save system weight.

Table 1. Summary of Results

	18-mm AN/PVS-5 Goggle Objective Lens Without Glass Faceplate	Partial Modification of AN/PVS-5 With GEN III Faceplate (Curved)	Full Modification of AN/PVS-5 With GEN III Faceplate (Flat)	MT/RR-001 Objective Lens With GEN III Faceplate (Flat)
Spectral region, μ	0.55-0.85	0.7-0.9	0.7-0.9	0.7-0.9
Field of view, degrees	40	40	40	40
EFL, mm	26.64	26.58	26.55	26.24
F/no.	1.33	1.35	1.30	1.25
T-no.	1.46	1.48	1.43	1.42
Full field rel. illum., percent	70	65	60	50
MTF at 30 lp/mm, percent	60	68	81	89
Distortion, percent	-7.29	-7.05	-7.05	-4.87
Glass weight, grams	57.19	48.90	50.75	28.28
Length, mm	51.51	45.59	48.44	40.02

4. RECOMMENDATIONS

1. Develop and build a glass prototype goggle objective lens system specifically designed for use with flat faceplate, third generation image intensifier tubes.

2. Develop and build a glass/plastic prototype goggle objective system for the same application as 1.

3. Require 1 and 2 to have equivalent laboratory performance.

4. Specify 1 and 2 to have length, weight, and projected manufacturing costs less than for current goggle objective systems.

5. Carry out environmental field test of both 1 and 2 incorporated into a GEN III goggle system or equivalent.

6. Examine the effects of 5 on a glass/plastic prototype objective with human response and laboratory tests.

In the course of developing the prototypes of 1 and 2, focal length, field of view, and distortion results may not be compatible with existing goggle eyepiece systems. The concurrent development of less costly, lightweight eyepieces compatible with the prototype objective lenses should be considered. This will permit advantageous changes in focal length and field of view while ensuring the maintenance of a distortionless system.

Appendix A

LENS PRESCRIPTIONS

Table A-1. Lens Prescription, AN/PVS-5 Goggle Objective

	Radius of Curvature, mm	Thickness, mm	N_d	V_d
	26.82			
Element 1		4.40	1.728	28.7
	72.61			
		1.29		
	26.82			
Element 2		3.90	1.734	51.7
	58.74			
		2.34		
	-32.17			
Element 3		1.70	1.785	26.1
	18.93			
		4.17		
	43.00			
Element 4A		5.80	1.734	51.7
	-11.83			
Element 4B		1.00	1.698	38.6
	-101.54			
Element 4C		3.00	1.697	55.4
	-27.73			
		3.00		
	22.99			
Element 5		5.60	1.788	47.4
	-41.45			
		2.00		
	-28.14			
Element 6		2.40	1.654	33.7
	33.7			

Table A-2. Lens Prescription, Partial Modification of AN/PVS-5 With GEN III Tube Faceplate

	Radius of Curvature, mm	Thickness, mm	N_d	V_d
Element 1	26.886 72.745	4.405	1.728	28.7
		1.281		
Element 2	26.886 58.870	3.898	1.734	51.7
		2.349		
Element 3	-32.243 18.975	1.709	1.785	26.1
		2.606		
Element 4A	33.082 -26.046	4.234	1.734	51.7
Element 4B	14.066	1.175	1.698	38.6
Element 4C	-39.203	5.446	1.697	55.4
		0.507		
Element 5	24.303 -46.189	4.232	1.788	47.4
		6.060		
Element 6	-23.357 366.722	5.657	1.785	25.8
		2.032		
Faceplate	-44.274 ∞	5.281	1.487	65.2

Table A-3. Lens Prescription, Full Modification of AN/PVS-5 Goggle Objective With GEN III Tube Faceplate

	Radius of Curvature, mm	Thickness, mm	N_d	V_d
Element 1	28.043 258.664	3.689	1.728	28.7
		0.391		
Element 2	26.692 43.659	4.275	1.734	51.7
		1.773		
Element 3	-67.591 17.539	1.683	1.785	26.1
		7.924		
	25.998			
Element 4A	-32.336	5.280	1.734	51.7
Element 4B	17.059	0.979	1.706	30.8
Element 4C	-45.585	6.364	1.697	55.4
		0.082		
Element 5	27.576 -60.778	7.533	1.788	47.4
		2.861		
Element 6	-20.048 27.824	3.404	1.549	45.4
		2.199		
Faceplate	∞ ∞	5.678	1.487	65.2

Appendix B

ABBREVIATIONS, ACRONYMS

BKFC	Paraxial system backfocus
COMA	Transverse tangential coma--3rd order
COMA5	Transverse tangential coma--5th order
DIST	Fractional distortion--3rd order
DIST5	Fractional distortion--5th order
ECOMA	Transverse eliptical coma
FCLN	Equivalent focal length
FNUM	F/number
GSHT	Gaussian image height
H	Object height
L/M-IMAGE	Slope of chief ray at image
OBJD	Object distance
OVLN	System length (first surface to paraxial image plane)
P	Primary light
PA	Transverse primary axial color--1st order
PETZ	Transverse Petzval blur--3rd order
PETZ5	Transverse Petzval blur--5th order
PL	Transverse primary lateral color--1st order
REN	Radius of entrance pupil
REX	Radius of exit pupil
S	Secondary light
SA	Transverse secondary axial color--1st order
SAGT	Transverse sagittal blur--3rd order
SAGT5	Transverse sagittal blur--5th order
SL	Transverse secondary lateral color--1st order
SOBSA	Transverse sagittal oblique spherical
S-P COLOR	Transverse secondary lateral color
SPHR	Transverse spherical--3rd order
SPHR5	Transverse spherical--5th order
SPHR7	Transverse spherical--7th order
S-T COLOR	Transverse primary lateral color
T	Tertiary light
TANG	Transverse tangential blur--3rd order
TANG5	Transverse tangential oblique spherical
TEN	Distance from first surface to entrance pupil
TEX	Distance from last surface to exit pupil
UK	Slope angle of axial ray at last surface
UKBAR	Slope angle of chief ray (full field) at last surface
UO	Slope angle of axial ray at object
UOBAR	Slope angle of chief ray (full field) at object

ABBREVIATIONS, ACRONYMS (Cont.)

XK	Sagittal ray height at last surface
XO	Sagittal ray height at object
YEN	Tangential height of ray at entrance pupil
YEX	Tangential height of ray at exit pupil
Y-IMAGE	Tangential ray height at image
YK	Tangential ray height at last surface
YO	Tangential ray height at object
Y1	Tangential height of axial paraxial ray at first surface
Y1BAR	Tangential height of chief paraxial ray at first surface